DECISION SUPPORT FOR BIDS IN INTERNATIONAL PLANT ENGINEERING

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Abstract

The demand for large-scale plants has increased rapidly in recent years. In 2008, the worldwide order volume totaled 350 billion Euro. Due to the worldwide economic slowdown since mid-2008, international plant orders have been falling dramatically resulting in increasing competition and high pricing pressure in the world market. Facing the hard challenge, plant constructors develop new manufacturing strategies worldwide.

Manufacturing plant components in low-wage countries typically reduce costs while lengthening project durations. The trade-off between plant project costs and duration is determined by location decisions, which are constrained by compulsive technology transfer and local content requirements.

Since a low bid price is crucial for the successful acquisition of a plant contract, plant industry aims at estimating the lower limit of the bid price by minimizing plant project costs under a given due date of delivery. The minimization of production and transportation costs with respect to the choice of location refers to the international facility location problem. The scheduling of international project activities deals with the multi-mode resource-constrained project scheduling problem. Both problems interact with each other by means of production and transportation time: The choice of location determines the time needed to produce and transport a subsystem or a component of a plant and therefore affects the project duration. In turn, to keep a tight project due date, location decisions resulting in shorter activity durations are favored, which typically increases costs.

In consideration of this interdependency, a mixed-integer optimization model is developed, which combines the location choice problem and the project scheduling problem to support decision-making in the plant bidding and negotiation procedures. In order to evaluate the model with respect to the maximum solvable project size, ProGen benchmark suits developed in the field of the resource-constrained project scheduling problem are used. To match the special problem domain in large-scale plant engineering, some parameters from ProGen are modified and some are added. To solve problems with large size and high complexity, a solution method using the Branch & Bound paradigm is

developed. The computational results demonstrate the advantage of the solution method in comparison with the application of the commercial software package ILOG CPLEX. Finally, the decision support of the developed model for bidding and negotiation is demonstrated in an application case using real data from an international plant manufacturing company.

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List of Notations

ε_{NET} tolerated complexity deviation, page 78

ε_{RF} tolerated resource factor deviation, page 78

C_{min} the minimal cost, page 72

d_j duration of job j, page 78

d_{jm} duration of activity j in country m, page 72

d_j duration of activity j, page 89

EFT_{jm} the earliest finish time of activity j in country m, page 72

EFT_j the earliest finish time of activity j, page 89

G estimated market value of a large-scale plant as reference to meet the expected LCR, page 72

g_{iljm} transport duration between j and its immediate predecessor i, if i is produced in country l and j in country m, page 72

J number of activities / components j ($j = 1, \dots, J$) in a project, page 72

k_{jrm} per period usage of resource r to perform activity j in country m, page 72

K_{rm} per period availability of resource r in country m, page 72

LFT_{jm} the latest finish time of activity j in country m, page 72

LFT_j the latest finish time of activity j, page 89

M number of countries m ($m = 1,\ldots,M$), $M \geq 2$, page 72

M_j number of modes of job j, page 78

N nonrenewable resource, page 78

P_1^N probability to choose a function reflecting a constant level of consumption with increasing duration, page 78

P_2^N probability to choose a function reflecting a decreasing level of consumption with increasing duration, page 78

P_1^R probability to choose a function reflecting a constant level of usage with increasing duration, page 78

P_2^R probability to choose a function reflecting a decreasing level of usage with increasing duration, page 78

P_J number of finish activities, page 78

P_j number of predecessors of activity j, page 78

p_{jm} production/procurement costs of the component j in the country m, page 72

PT the fastest possible project completion time, page 90

Q the given LCR proportion, $0 \leq Q \leq 1$, page 72

Q_N number of a nonrenewable resource requested, page 78

Q_R number of a renewable resource requested, page 78

R number of the renewable resources $(r = 1, \ldots, R)$, page 72

S_1 number of start activities, page 78

S_j number of successors of activity j, page 78

T upper bound for the project's makespan, page 89

T_{due} project due date with period $t = 1, \ldots, T_{due}$, page 72

T_{ij} transport duration between j and its immediate predecessor i, page 89

T_{lb} the project earliest finish time, page 91

T_{opt} the optimal time resulting from calling CPLEX to solve scheduling problem, page 91

T_{ub} the project completion time under consideration of resource constraints, page 91

U_N demand for a nonrenewable resource, page 78

U_R (per period) demand for a renewable resource, page 78

V_j index number of the immediate predecessors of j, $i \in V_j$, page 72

w_{iljm} transportation cost for i from country l to country m, where j is produced, page 72

x_{jm} the binary decision variable, page 72

y_{iljm} the binary decision variable, page 72

z_{jmt} the binary decision variable, page 72

z_{jt} the binary decision variable, page 90

List of Abbreviations

AACE	American Association of Cost Engineers
ANSI	American National Standards Institute
AON	Activity-On-Node
B&B	Branch & Bound
CEPCI	Chemical Engineering Plant Cost Index
CIS	Commonwealth of Independent States
CP	Critical Path
CPM	Critical Path Method
EFT	Earliest Finish Time
EST	Earliest Start Time
EU	European Union
ISO	International Organization for Standardization
ITB	Invitation to Bid

LB	Lower Bound
LCR	Local Content Requirement
LFT	Latest Finish Time
LIFO	Last-In, First-Out
LST	Latest Start Time
MIP	Mixed-Integer Programming
MMRCPSP	Multi-Mode Resource-Constrained Project Scheduling Problem
MODDEC	Model Decomposition
MODINT	Integrated Model
MPM	Metra Potential Method
NC	Network Complexity
PBS	Product Breakdown Structure
PERT	Program Evaluation and Review Technique
PSPLIB	Project Scheduling Problem Library
RCPSP	Resource-constrained Project Scheduling Problem
RF	Resource Factor
RS	Resource Strength
SMRCPSP	Single-Mode Resource-Constrained Project Scheduling Problem

TCH	Tons of Cane per Hour
UB	Upper Bound
USD	U.S. Dollar
VDMA	German Engineering Association
WBS	Work Breakdown Structure

Part I.

Concept

1. Introduction

In recent years the number of orders for large-scale plants built by German plant manufacturers has increased rapidly. In 2008, the order volume totaled 32.8 billion Euro representing approximately 20 percent of the world market volume (Figure 1.1). Incoming orders of large-scale plants for German manufacturers consist of an international part and a domestic part. Since 2001 the international part has dominated with a share of more than 75 percent. In 2008, the international orders came from 113 countries and reached 80 percent of total orders obtained by German plant manufacturers (Gottwald et al., 2009) (Figure 1.2).

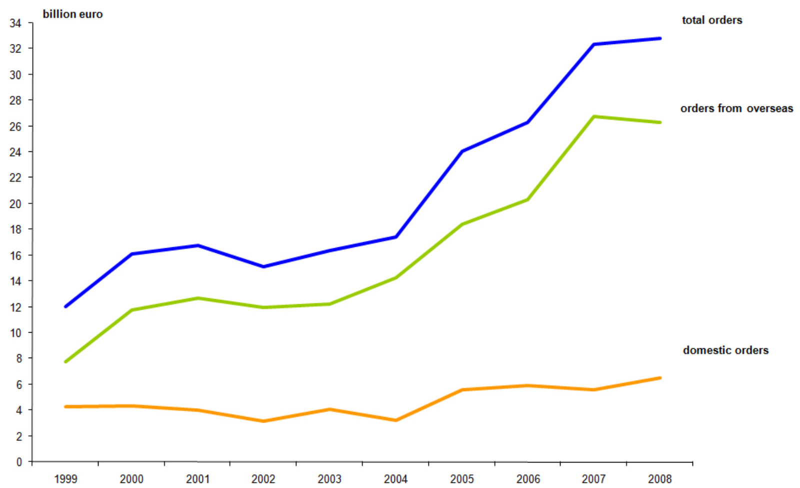


Figure 1.1.: Orders of large-scale plants with German manufacturers (Gottwald et al., 2009)

This trend dominated by oversea orders is expected to continue in the long term due to the increasing demand in global markets and saturation of demand in the domestic market (Gottwald et al. 2007, 2008, 2009):

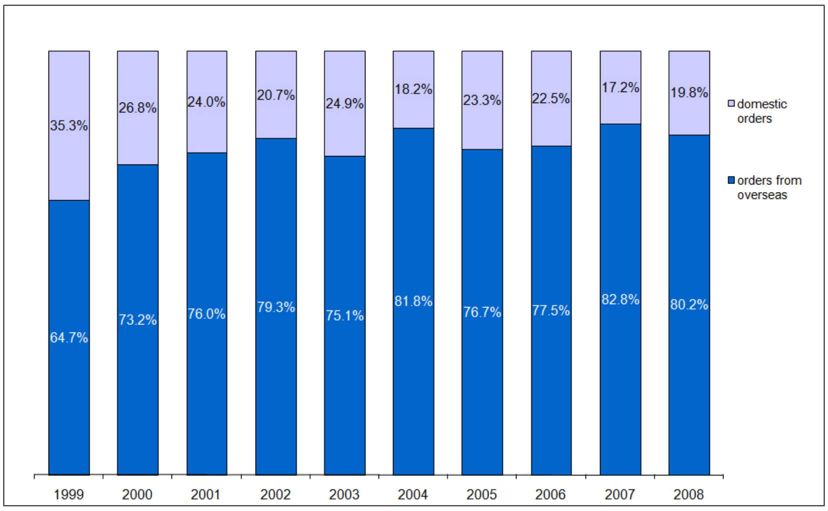


Figure 1.2.: Orders from overseas dominate the total orders (Gottwald et al., 2009)

- The economic growth in the Asian Pacific region, especially in China, makes a major contribution to this performance. In 2004, almost half of all German metallurgy plants and rolling mills were exported to China (Heymann, 2005). Since 2002, China has been ranked first on the list of the most important customer countries for German plant manufacturers. In 2007, China placed plant orders of 2.8 billion Euro, almost three times as much as those from the USA.

- In recent years, numerous countries in the Middle East as well as North America have achieved large export surpluses from raw material exports. With these revenues more new plants have been ordered to expand process industries in those countries.

- Because of the high prices of energy, raw materials and metals, the plant industry strives for plants with high energy efficiency and productivity.

- The environmental regulations of the European Union (EU) force the EU members to invest for replacement and retrofit equipments.

- Due to high operating costs in industrialized countries, investments have increasingly shifted to emerging countries resulting in a high demand for plants there.

Although the plant industry benefits from the rapidly increasing plant demand in the last five years, the global economic slowdown affects the plant industry significantly. Since mid-2008 the global economy has suffered a downturn. The global economic growth slowed to 3.4 percent in 2008 and has reached its lowest level since 2002. Whereas the plant demand rose by 15 percent in the first half-year compared to the same period in 2007, the number of orders sank by 11 percent in the second-half year of 2008 (Gottwald et al., 2009). The reasons were manifold: large industry countries such as the USA and Japan suffered in the recession and reduced their investments dramatically due to the decline in sales. Although the economic situation in some emerging countries was still positive in 2008, investments on new plants were cut or fell in response to the economic crisis. For countries relying on financing, the realization of projects became much more difficult as a result of the global banking crisis. Finally, raw material owners must consider reduced budgets and even the well-financed clients held off on investing and hoped to get a decreasing plant price. The impact of the financial crisis and the subsequent economic downturn lead to considerable uncertainty for clients of industrial plants, for banks and other investors as well as the large-scale plant industry itself.

Under the economic decline competition becomes much more intense (Gottwald et al., 2008, 2009):

- A large number of suppliers compete for a limited number of orders with aggressive prices leading to significant pricing pressure in the plant industry.

- In addition, suppliers from emerging countries have become new competitors by developing their technologies with acquired know-how. Those suppliers are able to take advantage of various favorable domestic policies (e.g. advantageous taxation politics, financial support and export credit insurance), which ultimately translate into their competitive pricing.

- Furthermore, the Euro's appreciation makes the situation much worse, since exporters' goods from European Economic and Monetary Union become more expensive. The export growth rate for German machinery constructors decelerated to 4 percent in 2007 from 7 percent in 2006

(Fraher and Thesing, 2007). In 2008, the effective exchange rate of the Euro increased 4.7 percent compared to 21 currencies, and increased even 7.3 percent compared to the US Dollar (Wirtschaft aktuell, 2009).

- In order to realize quick amortization of investment and reduce financial risks, plant buyers are striving for shorter project durations. According to the German Engineering Association (VDMA) - the largest association representing the capital goods industry in Europe - a shortage of 30-50 percent of former project duration has been observed; however, a further reduction is expected.

- Due to the enormous price increase of metals and other materials, the requirement of local manufacture of less technology-intensive but material-intensive parts has increased rapidly by ordering countries in recent years. In some major ordering countries the local content reaches even 70 to 80 percent of the total plant value. The higher such a requirement is, the larger the risk of the uncontrolled drain of know-how becomes for a plant manufacturer.

The high competition makes the decision-making process complex during the plant engineering. In the plant manufacture industry products are highly customized and therefore produced as projects in a make-to-order manufacturing (Backhaus, 2007). To win an order, a plant manufacturer typically submits a bid, which involves terms including technical specifications, prospected bid price and project completion time. The main objective of the bid proposal manager is to achieve an effective trade-off between the bid competitive value on the side of client expectations and the project baseline in term of project time, cost and performance constraints requiring a great deal of time and financial effort. Mistakenly calculated costs reduce profits and even result in losses. Inaccurate time estimates lead to delays in the subsequent implementation and may cause big losses.

Due to the international nature of orders and intensive competition in the global market, bid calculation and project scheduling become much more complex. Bid calculation is based on plant costs. The worldwide distribution of production locations can impact on the plant costs, so that the choice of location is considered in the bid calculation. The production time of plant components also depends on the location choice. Thus, the decisions of location and project scheduling should be integrated in the bidding phase already, which is still missing in practice.

Since usually the lowest bidder wins the contract, bid calculation plays an extremely important role in the bidding process. The objective of this research is to minimize plant costs in consideration of constraints, such as a given project deadline, the requirement of local content, know-how protection, and resource availability. The optimization problem is analyzed from the viewpoint of the potential contractor, i.e. plant manufacturers.

This dissertation research is challenging for a variety of reasons. First, it tackles both the international facility location problem and the resource-constrained project scheduling problem. Second, it integrates a full range of strategic and tactical decisions in operations of plant projects. Third, it applies researches of major fields: economic modeling, project planning, solution techniques as well as operations management. This research can impact manufacturing strategies which are critical to the competitive performance of German plant manufacturers competing in global markets.

Five major tasks are handled in this dissertation:

1. Identify challenges in the bidding process of international plant projects.
2. Present the interaction of location choice and project scheduling in international plant engineering.
3. Develop an optimization model for estimating the lower limit of a bid price under complex constraints.
4. Develop tractable solution algorithms to generate optimal solutions for problems of large size and complexity using well-known benchmark data sets in the field of resource-constrained project scheduling problems.
5. Verify the model and the solution method using real project data provided by a global plant manufacturer to improve the understanding of the problem structure and to demonstrate the effectiveness and the decision support for bidding and negotiation of the model and solution methodology.

This dissertation consists of two parts. The first part consists of four chapters which offer a comprehensive overview of the most important issues of international large-scale plant engineering. The second part includes five chapters which focus on modeling and solving an optimization problem, which enables plant manufacturers to minimize plant costs in consideration of complex constraints.

Figure 1.3 provides an overview of the structure of this thesis:

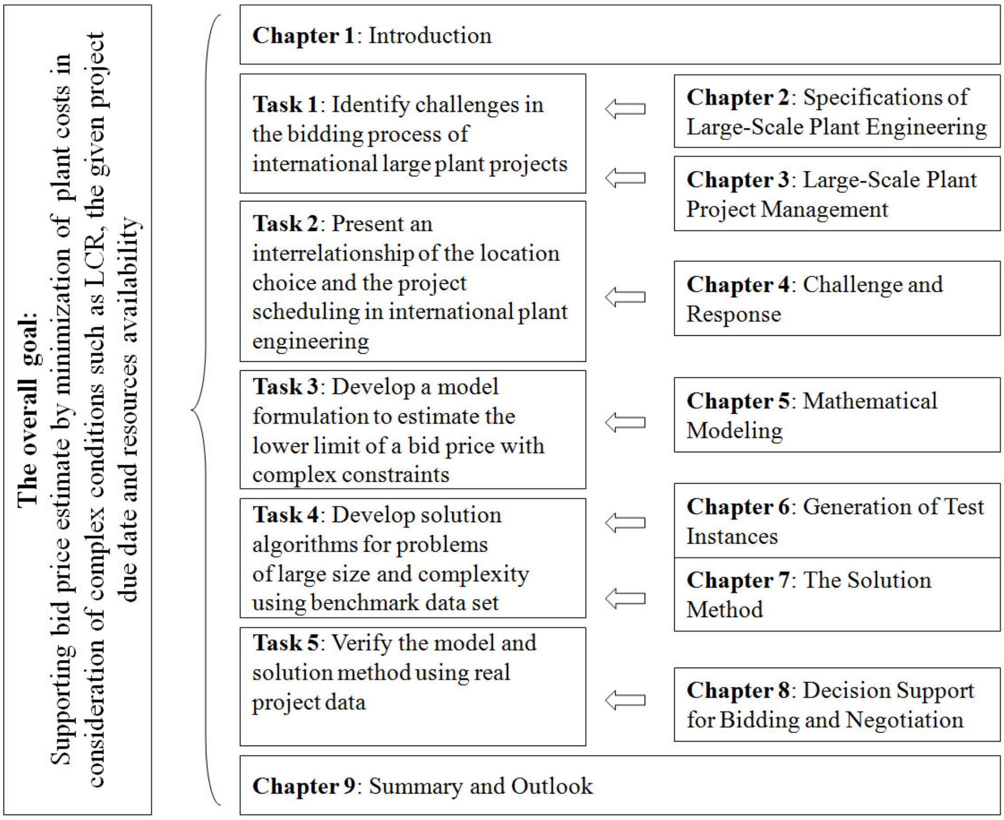


Figure 1.3.: Structure of the thesis

Chapter 2 provides an overview of large-scale plant industry in Germany, including some definitions, specifications and the market segments. Especially the process plant industry is introduced in detail. The importance of managing plant project is addressed to receive more consideration of project management issues in plant engineering.

Since plant engineering is performed in form of a project, a detailed description of the project life cycle is given in Chapter 3. The bidding process and its important components, i.e. cost estimates and project scheduling, are highlighted due to the importance of winning a contract. This chapter reveals the complexity of bid calculation and project scheduling.

This complexity increases due to the international nature of plant business and the hard competition in global markets. Therefore, the challenge issues for the German plant industry are addressed in Chapter 4. We first describe the current situation of German plant industry. The competition trend and the resulting challenges in large-scale plant industry are then discussed. This challenging situation in plant business is confirmed by a large plant manufacturer active in global plant market through a business case. Against this background, new requirements on the bidding procedure have to be met. Particularly the location choice and project scheduling need to be integrated in the bidding process in order to estimate a reasonable low bid price under complex constraints.

In Chapter 5, to integrate the location choice and project scheduling, literature on both topics is reviewed. On this basis, a mathematical model is developed, which integrates the international facility location problem and the multi-mode resource-constrained project scheduling problem. By minimizing the project costs, the lower limit of a bid price is calculated. Constraints from both location choice and project scheduling are considered.

In Chapter 6, test instances are defined according to the benchmark data sets from ProGen to evaluate the mathematical model. Some modifications and extensions are made to match the problem at hand.

In Chapter 7, we propose a solution method based on the Branch & Bound paradigm to solve problems of large size and complexity. The computational results demonstrate the advantage of the solution method.

In Chapter 8, the model and the solution method are validated with real data from an ongoing plant project to demonstrate decision support of the model for the bidding and negotiation processes.

Finally, Chapter 9 draws some conclusions. It provides a summary of the main results obtained in this dissertation and identifies further research topics.

2. Specifications of Large-Scale Plant Engineering

This chapter provides an overview of the large-scale plant industry and plant engineering. It starts with some basic definitions, followed by discussions on features of industrial plants. The important role of the German plant industry in the national economy and its segments are addressed in Section 2.2, especially the process plant sector is described in detail to give a deep insight into large-scale plants. In Section 2.3, plant engineering and its differentiating factors to general engineering are illustrated. This chapter ends with the requirement of a more focused project management approach in large-scale plant engineering in Section 2.4.

2.1. Definition

Before giving an in-depth coverage of a large-scale plant, the notion of an industrial plant has to be clarified. There are different definitions of the term "industrial plant" in science and practice. From the marketing's point of view, *Backhaus* defines an industrial plant as a range of goods and services provided by one or several suppliers in a closed bid to satisfy complex demands (Backhaus and Weiber, 1993). This definition is based on the form and the purpose of a plant purchase.

In consideration of the object and its configuration, *Schiemenz and Schiller* define a plant as an interconnected, complete plant system integrating different subsystems and components (Schiemenz, 1992; Schiller, 2000).

According to the definition of the large industrial plant manufacturers' group, a division of VDMA, a large-scale industry plant is an industry plant using process engineering technologies and with a financial volume more than 25 million Euro (Gottwald et al., 2008).

The main differences between a large-scale plant and the classic machine and plant construction are process technology and engineering. A large part of a large-scale plant is manufactured by using process technology and engineering (Ilgen, 2001).

Based on these definitions, a large-scale plant is characterized by the following features:

- A large-scale plant satisfies individual demands, so that it is produced in make-to-order manufacturing. A plant is sold prior to its construction.
- A plant is provided by one or several suppliers in form of a bid.
- A whole plant can be understood as a complete plant system. It integrates different components, which are interconnected by process technology. A component can be a subsystem, assembly, subassembly or other major element of an end item providing a self-contained functionality (Wideman, 2006). Self-contained functionality means that a component should be functionally complete so that it can perform its function without depending on other components (Schiller, 2000). The structure of a plant is shown in Figure 2.1.
- Since a plant can only function as a whole by virtue of the interdependence of its parts, the subsystems need to be interconnected with each other, which requires special know-how and results in high operating expense. In many cases plant suppliers always need to develop new technology or new components for plants to achieve competitive advantages (Schiller, 2000).

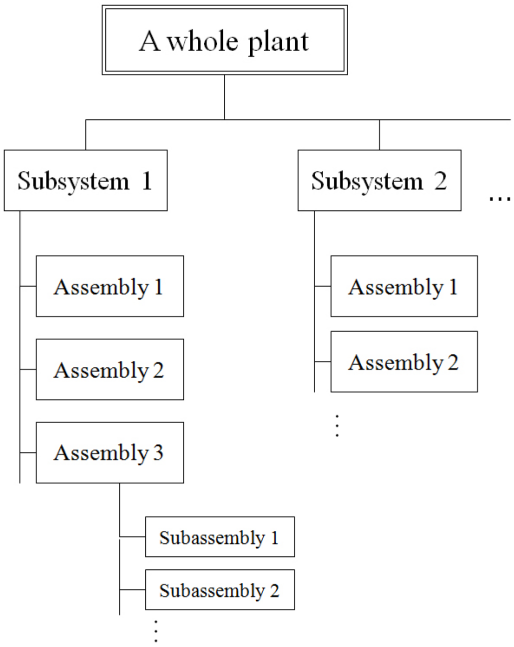


Figure 2.1.: Structure of a plant (Schiller, 2000)

- The large amount of interdependent components and high novelty result in a high degree of complexity. According to Balck (1996), the features of plant complexity are unclear, networked, dynamic, intransparent, probabilistic and instable. Complexity levels of a large plant are shown in Figure 2.2.

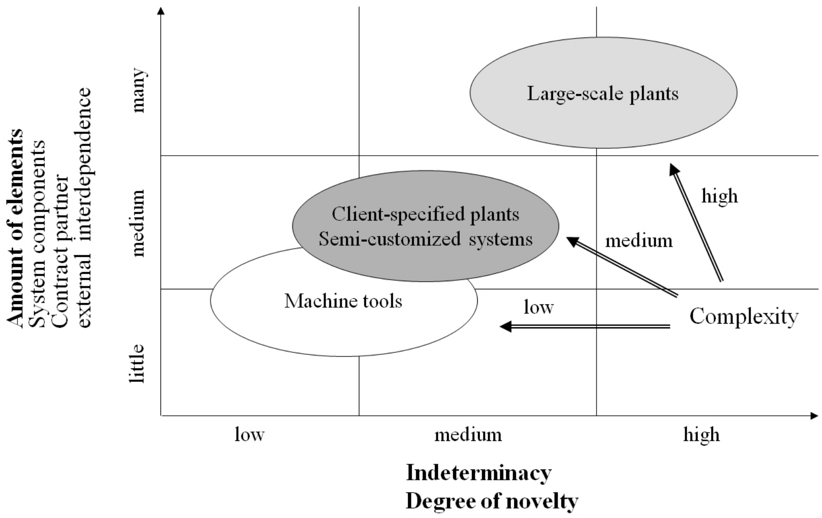


Figure 2.2.: Complexity of a large-scale plant (Balck, 1996)

- Plant engineering is usually undertaken in form of a project with a clearly defined due date. Due to complexity and high technology, the duration of a plant project averages about three years (Gottwald et al., 2005).
- Due to high operating expense, plant projects typically require massive capital investment (Watermeyer, 2002).
- Because of the generally high costs and the contribution of an installed plant to the social well-being of a country, its government attempts to affect industrial plant construction with compulsive measures, such as import quotations, import duties and import certificates.

2.2. German Large Plant Industry and Segments

The German large-scale plant manufacturing industry is a major sector of the economy with an annual new order volume of over 26 billion Euro (average 2004-2008) and a world market share of roughly 20 percent. In Germany, over 58,400 highly qualified employees were engaged in this industry in 2008. The plant industry also generates valuable impetus for the medium-scale mechanical engineering sector as a whole: sub-contracted services and supplied components account for around 75 percent of its total volume, and approximately 170,000 additional jobs in the companies of subcontractors and suppliers depend on the various projects (Gottwald et al., 2009).

By entering new markets and engagement in the developed markets, the large plant industry contributes considerably to the expansion of Germany's international economic relations. Frequently, this industry is pioneer for the emerging markets' industrial development and at the same time pathfinder for the succeeding export industry.

Large industrial plant manufacturers are defined as companies capable of processing one or more client-specific industry plant projects annually with a volume of more than 25 million Euro each (Gottwald et al., 2009). They must have the comprehensive technical and process expertise necessary to handle all aspects of the entire project, including the planning, designing and engineering of the plant and the production or international procurement of facilities and equipments, along with delivery, installation, commissioning and provision of financing. Manufacturers of power stations, steelworks and chemical plants are examples of large-scale plant engineering contractors (Gottwald et al., 2009). German plant manufacturers have an extensive range of expertise and experience in plant manufacturing, especially of complex plants. As shown in Table 2.1, some projects have a considerable complex scope of deliveries and services, and reach a financial volume of more than 500 million Euro. Such a project has a high requirement on the handling resources, the financial power and competence in granting of security and risk management of contractors.

Table 2.1.: Large projects performed by German plant manufacturers between 2005 and 2008 (Gottwald et al., 2009)

Large project 2005-2008				
Large projects (amount)	2005	2006	2007	2008
larger than 500 million €	1	3	3	2
larger than 125 million € to 500 million €	24	14	30	35
larger than 50 million € to 125 million €	39	54	68	77
25 to 50 million €	68	75	98	98
Total	132	146	199	212
Large projects (in billion €)	2005	2006	2007	2008
larger than 500 million €	0.5	2.4	2.2	1.5
larger than 125 million € to 500 million €	5.1	3.2	7.0	7.2
larger than 50 million € to 125 million €	3.1	4.0	5.2	6.4
25 to 50 million €	2.4	2.6	3.5	3.4
Total	11.1	12.2	17.9	18.5

The German large-scale plant manufacturers deliver plants for over twenty different industries. In the following we focus on plants for the process industry, including power stations, steelworks and rolling mills, chemical plants, electrical equipments, construction materials plants, paper and cellulose plants, air and gas liquefaction plants, gas generation plants, and plants for raw materials production and processing (Gottwald et al., 2009). In all industries, German manufacturers set the standards for plant productivity and energy efficiency, and enjoy a good reputation in the global plant market.

In Table 2.2, the market share of major segments in 2006 and 2007 is shown.

Table 2.2.: The market share of major sectors in 2006 and 2007 (Gottwald et al., 2008)

	2006		2007	
Plant type	million €	%	million €	%
Power plants	8,945	34	10,955	33.9
Steelworks and rolling mills	3,261	12.4	5,729	17.7
Chemical plants	2,661	10.1	3,890	12
Electrical equipments	2,277	8.7	3.286	10.2
Construction materials plants	829	3.2	1.112	3.4
Paper and cellulose plants	457	1.7	820	2.5
Air and gas liquefaction plants	1.904	7.2	770	2.4
Gas generation plants	1.011	3.8	543	1.7
Raw material production & processing	404	1.5	487	1.5
Other plants	1121	4.3	1230	3.8
Spares and small orders	3.408	13.0	3.535	10.9
Total	26.278	100	32.357	100

In the following, a detailed description of the above-mentioned segments, their market situations and important clients is given (Gottwald et al., 2009).

Power plants

The power plant sector is the most important sector for the large plant industry. 2008 was a successful year for the power plant manufacturers. Different from early boom stages, the high demand results not only from certain technologies or regions, but also from all client regions and different power generation types. In 2008 this industry achieved a record order volume of 9.9 billion Euro and increased by 40% compared to the average level of the last ten years. The most important clients were the industry countries with a share of 48% in 2008 and 55% in 2007. The long-term service contracts also play an important role for this sector.

Steelworks and rolling mills

The demand on steelworks and rolling mills reached a very high level in 2008. The orders increased by 4% to achieve 5.5 billion Euro. The key markets for this sector are the BRIC-countries, i.e. Brazil, Russia, India and China. Orders from these four countries in 2008 totaled 3.1 billion, almost 56% of all orders in this segment. Further important countries were Eastern Europe and the Commonwealth of Independent States (CIS countries), where the orders increased by 156% to 1.6 billion Euro. The essential reason for this boom was the environmental regulations of the EU, which forced the EU members to invest for replacement and retrofit equipments. In addition, this sector benefited from economic growth and the industry regeneration in Russia. The increasing energy demand of the Russian economy requires investment in the power plants resulting in quintuple orders with the value of 932 million Euro.

Chemical plants

The German chemical plant manufacturers received incoming orders with a value of 3.2 billion Euro in 2008. The foreign share in chemical equipment manufacturing was 92% and hence significantly above the 80% average of overall large-scale plant engineering. The most important market for German chemical equipment manufacturers over the past few years is Egypt with an order volume of 2.2 billion Euro in the period from 2003 to 2007.

Electrical equipments

The manufacturers of electrical equipment benefited from an order volume of 2 billion in 2008. The largest markets are in the industrialized countries and in the Middle East, where a massive expansion of network infrastructure is further invested. Generally, the demand on energy-technical equipments and automation technology in most buyer industries is still active. In the economy-sensible sectors such as metal industry, oil and gas sector the orders fell off. However, revenues are improved due to sourcing in countries with lower costs and through optimization measures.

Construction material plants

In spite of stagnating or even declining construction business in many countries in the last years, the cement plant orders increased by 12% to 1.2 billion Euro. Since 2004, the order volume has increased almost quintupled. The manufacturers succeeded to compensate the decline in industry countries (minus 58%) and in the Middle East (minus 73%) by an increase in emerging countries such as Ukraine, Russia, Guatemala and Vietnam.

Paper and cellulose plants

The demand on cellulose and paper plants sunk in 2008, but was still above the average level of the last ten years. The sector benefited from the expansive world trade in the first half of the year, which resulted in high demand on packaging paper. While clients from West Europe invested in the maintenance and strengthening of their capacities in 2008, new plants were ordered by the countries with economic growth, e.g., South Africa and India. Over the years, China has been the most important market for cellulose and paper plants. In 2008, China placed an order volume of 232 million Euro, which indicated a decrease compared to 2007. However, the capacity expansion of the Chinese paper industry will keep in time resulting in further demand on cellulose and paper plants.

Air and gas liquefaction plants

Air and gas liquefaction plants were strongly in demand from January to September 2008. The orders in the whole year increased by 55% to 958 million Euro.

In conclusion, the German plant industry has achieved major sales successes in recent years. The boom in plant sales results from the increasing demand in foreign countries, especially in the emerging markets due to the strong economic growth there and in countries with rich raw materials. The German plant manufacturers benefit not only from the global presence in form of production sites, sales offices and service enterprises, but also from their technologies enabling resource efficiency for client specifications and their competence in plant engineering.

2.3. Plant Engineering

Large-scale industry plant engineering is the combination and integration of different deliverables and services to a functional system (industry plant) to enable a process flow containing different interconnected process steps with the overall responsibility. Deliverables include basically plant sections, machines, instruments, components and connective elements (e.g. frames, pipelines, wirings) and software. Services include basically planning, financing, manufacturing and/or worldwide sourcing, construction, delivery, montage, commissioning, maintenance, documentation and training (Gottwald et al., 2009).

Plant construction in process plant industries involves the construction of physical plant facilities and material processing equipments, which include the manufacture of equipments, ranging from the larger components of a plant (such as distillation columns, evaporators, pressure vessels and dryers) to smaller components (such as pipework components, pumps, filters and valves) to control gear components (such as sensors, instrumentation and control computers) (Research and Markets, 2000). The type of equipment used in the process industries falls into certain specific categories, common to all plants. Apart from what we might call *off-the-shelf* standard components, such as pumps, compressors, pipe and pipe fittings, electrical switchgear and instruments, the rest of the plant is usually *custom built* for the specific project. Typical plant components in this category are presented as follows (Watermeyer, 2002):

- Process equipment items, in which material is transformed physically or chemically, e.g. crushers, reactors, screens, heaters, and heat exchangers. The process equipment is required to effect the physical and chemical changes and separations necessary to produce the desired products, and also to deal with any unwanted by-products, including waste, spillage, dust, and smoke.

- Materials transport and handling devices, by which the processed materials and effluents are transferred between the process equipment items, in and out of the plant or any intermediate storage, and by which solid products and wastes are handled.

- Materials storage facilities, which may be required to provide balancing capacity for feedstock, products, or between process stages.

- Process utilities, which are systems to provide and reticulate fluids such as compressed air, steam, water, and nitrogen, which may be required at various parts of the plant for purposes like powering pneumatic actuators, heating, cooling, and providing inert blanketing. Systems to provide process reagents and catalysts may be included as utilities, or as part of the process.

- Electric power reticulation, which drives process machinery, performs process functions like electrolysis, supplies lighting and powering for instrumentation and controls, and operates as a general utility.

- Instrumentation, which provides information on the state of the process and the plant.

- Structures (made of various materials, including steel and concrete), which support the plant and equipment in the required configuration, enclose the plant if needed, and provide access for operation and maintenance.

- Foundations, which support the structures and some plant items directly, and various civil works for plant access, enclosure, product storage, and drainage.

- Plant buildings such as control rooms, substations, laboratories, operation and maintenance facilities, and administration offices.

The design and construction of a process plant are relatively large and complex (see Figure 2.3), requiring the interaction of technical, commercial and construction knowledge and skills. Compared with the general field of engineering design and construction, the main differentiating factors are addressed in the following (Watermeyer, 2002):

- The unique design of each plant is the inevitable consequence of the need to optimize each application to its unique circumstances of feedstock, product, capacity and environment.
- Plants are built from hundreds of items of proprietary processing equipment.
- Both the plant design and construction specialist must interact at a lot of interfaces to produce a coordinated product.
- The nature of the industry served by process plants usually puts a high premium on early completion and operation.
- The project schedule cannot be generated in any mechanistic fashion. Invariably, the critical path can be shortened almost by taking various shortcuts (changing the schedule logic, employing more resources or working faster). These possible shortcuts come at a cost or risk, which must be balanced against the benefits.
- The plant must be constructed on site, to suit its site, wherever that may be.
- Furthermore, process plant construction typically involves considerable capital investment (Helmus, 2008).

All of these features have to be addressed during the plant engineering and its follow up. These features reveal the complexity of the plant engineering.

Figure 2.3.: A large-scale ethylene plant (Gottwald et al., 2007)

2.4. Importance of Managing Plant Projects

Due to the complexity of plant manufacturing, project management approaches for successful completion of a plant project should deserve much more consideration. However, despite its significant financial contribution to national economy, the process plant industry has largely been ignored by project management researchers (Fransoo and Donk, 2003; Zobel and Wearne, 2000).

Plant manufacturing is capital intensive. The costs of its products are usually heavily dependent on the initial capital investment. Thus, the accuracy of the capital estimate can be crucial to the success of a process plant project (Kerzner, 2009; Gerrard, 2000; Kharbanda and Stallworthy, 1988). In 1998, project management in the United States was a $850 billion industry, with a predicted growth rate of 20 percent annually (Bounds, 1998). For this amount of investment capital, cost control in capital projects is crucial. However, more than 15 percent of authorized projects run 50 percent or more over budget (Scott-Young and Samson, 2008). Minimizing project time is favored by clients and presents the competitive advantage of plant manufacturers, which is realized based on project scheduling approaches. Slow project execution may turn a promising investment opportunity into an expensive failure. Plant technical performance is another criterion for project success. Due to the unique design and the technical complexity, interdependency and interaction of plant project components should be integrated considered to produce a coordinated product. Production installations in the process industries are extremely costly, so that a high utilization with minimal maintenance shutdowns is necessary to maximize throughput and business returns (Scott-Young and Samson, 2008). Despite the importance of project management approaches for the plant project success and for gaining a competitive edge, research on minimizing costs, improving cycle time and plant operability in capital projects is scant (Scott-Young and Samson, 2008; Cooke-Davies, 2002).

In a word, project success criteria of costs, time and technical performance should be given more attention during managing a process plant project. In the following chapter we focus on how to manage process plant projects successfully using project management tools and techniques.

3. Large-Scale Plant Project Management

Typically, manufacturing of a large-scale plant is carried out in form of a project. Each project has its scope, specifications and constraints, which are considered during the project life cycle. In the large-scale plant industry, project management has been widely accepted as a powerful tool to face the challenges of project budget overrun, project delay and limited resources. In this chapter, an introduction of project management processes and management tasks during the project life cycle is given. We focus on the tasks related to project bidding and planning since they are particularly crucial for the project acquisition and execution. Among these tasks, bid calculation and project scheduling are addressed in detail. For more detailed information of project management we refer to Pinto and Slevin (1998), Kerzner (2005), Cleland and Ireland (2006), PMI (2008).

3.1. Definition of a Project

In the literature a large variety of definitions concerning the term *project* can be found. According to the definition of ISO 10006, a *project* is a unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective that conforms to specific requirements, including the constraints of time, cost, and resources. Projects differ from operations, such as manufacturing, in that operations are ongoing and repetitive, while projects are temporary and unique (PMI, 2008).

Summarizing different definitions, a project possesses the following typical characteristics (Shtub et al., 1994; Spinner, 1997; Pinto and Slevin, 1998; Wideman, 2004):

- A project has a specific, predetermined objective or set of objectives. Some of the objectives may be in conflict with each other, so that a prioritization and a trade-off between objectives are to be made.
- To achieve project objective(s), series of complex or interrelated activities have to be accomplished.
- A project has an approved budget. A project is located with a level of financial expenditures within which the deliverables are produced to meet the specified client requirements.
- A project represents a unique process, which has a clearly defined beginning and end (specified time to completion).
- Resources available for executing a project are restricted. At the start of a project, an agreed amount of labor, equipment and materials is allocated to the project.
- Projects entail a level of uncertainty and therefore carry business risks.

The objectives of a project can be grouped in three categories (Lock, 2007), (Cleland and Ireland, 2006) (see Figure 3.1):

1. Quality: The result of a project must fit the intended purpose. The specifications must be satisfied.
2. Cost: Projects need to be completed within budget and yield expected return on capital investments.
3. Time: The total completion of a project must take place on or before the deadline. Late completion could result in contract cost penalties and may damage the contractor's reputation. Furthermore, a delay of a project could occupy resources and therefore disrupt the contractor's following projects.

These three objectives are usually negatively correlated with each other: enhancing quality typically increases associated time and costs, a tight time constraint could increase costs and reduce quality, and a tight budget could increase time and lower quality. Therefore, it is important to make an effective trade-off between those objectives. This affects the priority in allocating scarce resources and the management's focus.

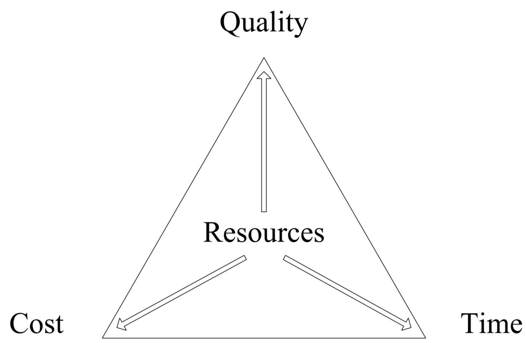


Figure 3.1.: Triangle of objectives

Project success is assessed on the triple set of cost, time, and quality (Kloppenborg and Opfer, 2002). In process plant industries, cost, schedule control and plant operability are regarded as important measures of capital project success, which indeed drive client satisfaction (Belout and Gauvreau, 2004). A project is considered successful if it is completed within its budget estimate, within its initial scheduled time frame, and performed as it is designed to (Kerzner, 2009).

Since achieving the quality requires competence in technical engineering and design, which is not the purpose of this dissertation, we focus on the cost and time in the sequel.

3.2. Project Life Cycle

The above stated objectives are considered and implemented through the project life cycle. The project life cycle refers to a logical sequence of activities to accomplish the project's objectives. Regardless of scope or complexity, each project goes through a series of phases during its life, from an initiation, followed by planning and execution until termination (Lock, 2007). Collectively, these phases are known as the project life cycle, which provides a framework for budgeting, resource allocation, and project scheduling. The project life cycle model is used to identify and understand the total breath and longevity of the project and the management functions involved in the project life cycle (Cleland and Ireland, 2006; Stuckenbruck, 1981). Project phases may vary in size and complexity. Also their names may differ depending on organizations. The life cycle model from the Project Management Institute provides a typical example (Wideman, 2004; PMI, 2008):

- In the *initiation* phase, the objectives of the project are agreed upon, the scope of the project is established, the initial organization is defined, responsibilities are assigned, and the assessment of situational factors is documented.
- In the *planning* phase, detailed work and risk management plans are developed, the organization is confirmed, staff assignments are made, and the budget and time frame are agreed upon. No significant amount of resources will be expended on the project until clear plans are in place and authorization to proceed has been received at the end of this phase.
- In the *executing/controlling* phase, the plans and controls are used to execute and manage the project during the project development and delivery work. As work proceeds, plans are expanded or refined as necessary.
- In the *closure* phase, the sponsor agrees to terminate the project. The project evaluation report is produced, and the included lessons learned can be applied to future projects to increase their probability of success.

Authors in some publications, e.g. Kerzner (2005), Cleland and Ireland (2006), suggested to organize project phases into industry-specific project cycles, since each industry sector has specific requirements, management tasks, procedures, and therefore has different needs for life cycle management methodology. According to Helmus (2008), the complete process plant project is divided into two phases, i.e. project planning and project execution.

Project planning: Within the context of project planning, it is to be decided whether, and if so, how a plant will be manufactured. The project planning phase comprises the following main processes (Helmus, 2008):

Inquiries/Invitation to Bid: The client identifies a need or a problem resulting in an Invitation to Bid (ITB), which is issued to the prospective bidders (contractors) for a bid/quotation/proposal to supply goods and/or services. An ITB may contain a statement of work, which addresses the scope of the project and outlines the tasks or work elements including but not limited to the following:

- physical or operational parameters requirements, e.g. size, quantity, weight
- deliverables the customer expects the contractor to provide
- a bid price
- payment terms the customer intends to use
- a time frame of the project
- deadline by which the customer expects potential contractors to submit proposals.

Once the ITB has been prepared, the client solicits proposals by notifying potential contractors that the ITB is available.

Bid/no-bid decision: The received inquiries or ITBs are evaluated according to the success chance, available technology and resources, competitor situation, profitability, risks etc. in order to decide the appropriate response. Blind bids without evaluating business opportunities result in high bid costs and a relatively low bid-win rate (number of bids won versus the number of bids submitted). The bid costs could reach five percent of the total project value and the bidder shall bear all these costs (The World Bank, 2006). In practice, just five to ten percent of all bids will result in contracts (Schiller, 2000). Therefore, it is very important to conduct a thorough opportunity and risk assessment before making a bid/no-bid decision.

Bidding: Once the decision for a bid is made, the bidding process from bid preparation to bid submission begins. Each bidder spends a great deal of time for developing solutions and for documenting the information demanded in the ITB. During the bidding process, cost forecasts and analyses play an important role. In order to assess the production costs for a planned plant as exactly as possible, so-called *basic engineering* has to be carried out. This consists of the design and optimization of the process concept and the materials concept, the implementation of a layout plan including main components, electric components and installation, as well as scheduling, and finally the determination of a bid price. On the basis of the basic engineering a bid is generated. The bidding process ends with the submission of bids to the client. The different bids obtained during the bidding process serve as the basis for the negotiation later on.

Contact negotiations and sign-off: The client compares the bids provided by different bidders and negotiates the contract conditions with selected bidders (Wideman, 2004). Finally, a contract is awarded to the lowest priced bidder meeting all requirements.

The activities during the project planning phase are summarized in Figure 3.2:

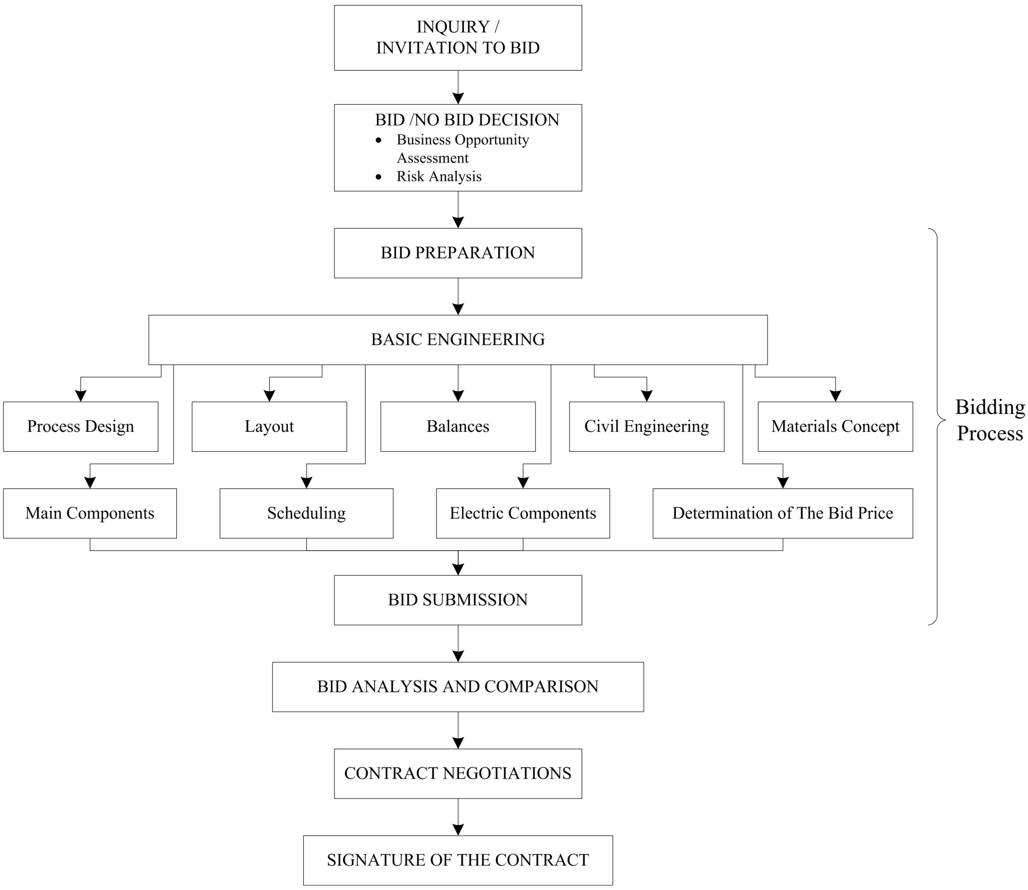


Figure 3.2.: Overview of the activities during the project planning phase (Helmus, 2008)

Project execution: The execution of a process plant project follows the project planning, i.e., after the starting signal for the construction has been given by the competent authority. The planning activity necessary for the project execution is known as *detail engineering*. Besides the planning steps, further activities including *procurement* and *montage* of the equipment as well as *commissioning* of the plant have to be carried out. The project is completed with *acceptance* after the successful *test*. Then the actual operation of the plant can start and the *warranty* is provided (Helmus, 2008). The important activities during the execution phase are presented in Figure 3.3:

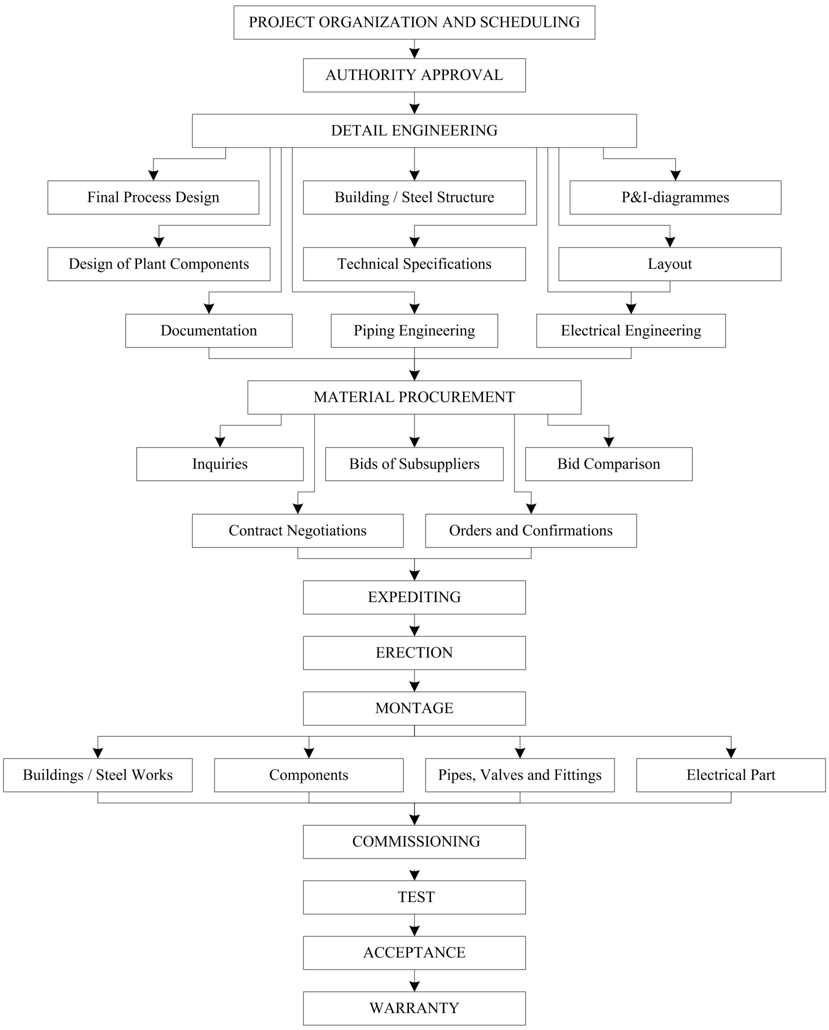


Figure 3.3.: Overview of the activities during the execution phase (Helmus, 2008)

The interface between project planning and project execution is the conclusion on the contract, in which all commercial and technical project details are stipulated.

In the process plant project life cycle, the planning phase plays an important role. Without efforts in the planning phase, no contract can be closed and therefore the project execution cannot take place. The planning phase determines the project scope, budget, time frame and other conditions, which guide the project execution and provide a baseline for project control.

The most crucial process in the project planning phase is the bidding process. Due to limited information, the bidding process involves high uncertainties and risks. The bid preparation is time-consuming and requires significant manpower, which may be in vain if the bid does not win a contract. Furthermore, clients almost set a tight time frame for bid submission, so that the time available for preparing a bid is limited. For very large technical projects, proposals are often due within thirty calendar days after the ITB's issuance (Gido and Clements, 1999).

Due to the importance of the bidding process, we focus on it in the following sections, especially its most essential activities:

- design of project deliverables in Section 3.3,
- cost estimating in Section 3.4,
- project scheduling in Section 3.5.

3.3. Design of Project Deliverables

As depicted in Section 2.3, besides the off-the-shelf standard components, the rest of the plant is normally custom built. The design of the custom-built project's product is performed in the basic engineering, which sets up the basis for the later price estimate and project scheduling. A project's product consists of components at several levels of breakdown, each of which delivers parts of the functionality of the project's deliverables (Wideman, 2006). Such a structure is called a Product Breakdown Structure (PBS). PBS is a hierarchical decomposition of product into components. Each level of the PBS represents an increasingly detailed view of the components.

The PBS helps to (IBM internal material, 2001):

- identify all work products and to designate which work products are deliverables (some work products, such as project management plans and status, are not deliverables);
- identify reusable work products and components, which support make-or-buy decisions;
- identify logical relationships, which assist to build the sequence;
- clarify the information for formulating estimates;
- create the Work Breakdown Structure (WBS).

While the PBS focuses on **what** is to be produced in the project, a WBS focuses on **how** the work products and project solution will be built. A WBS is a task-oriented family tree of activities, which organizes, defines and graphically displays the total work to be accomplished in order to achieve the final objectives of a project (Wideman, 2006). An activity presents an element of work performed during the course of a project. In the following, an activity is defined to represent the production or procurement of a component of a large-scale plant. An activity normally has an expected duration, an expected cost, and expected resource requirements. Therefore, a WBS is a system for decomposition of a project into manageable activities to provide a common framework for cost estimation, scheduling, and allocation of resources (IBM internal material, 2001).

3.4. Cost Estimating

On the basis of a WBS, plant costs can be estimated, which supports the determination of bid prices. The bid price is crucial to acquire a plant contact. When a bidder prepares a bid for a large-scale plant, one is generally competing with other bidders to win a contract. Therefore, a bidder needs to be careful not to overprice the proposed project, or else the customer may select a lower-priced bidder. However, the bidder must be equally careful not to underprice the proposed project to avoid the winner's curse[1] (Kagel and Levin, 2002); otherwise, he may make a loss rather than a profit or may have to request additional funds from the customer, which could be embarrassing and hurt the bidder's reputation (Gido and Clements, 1999).

The objective of the estimating procedure is to determine the optimal bid price, which a contractor could submit to give the best chance for winning a contract and making a profit. In order to make up leeway at forming a bid price, the lower limit of a bid price is to be known. The lower limit of a bid price is based on cost estimating (Kerzner, 2009).

An accurate estimate of capital cost is fundamental to the success of a project. The cost estimate serves not only for the purposes of identifying the magnitude of the investment and the bid price, but also later on as a tool for the cost control of the project to avoid cost overruns. Lots of projects have suffered from cost overruns (Flyvbjerg et al., 2003; Kharbanda and Stallworthy, 1988). A famous case was the building of the Sydney Opera House. It was completed some ten years later than first planned, at a cost some fifteen times the original estimate (Flyvbjerg et al., 2003; Kharbanda and Stallworthy, 1983).

To perform a manufacturing cost estimate properly, all cost elements for completing a plant must be considered.

3.4.1. Cost Elements

In order to understand cost elements, the following terms are used (Humphreys and Wellman, 1996):

- Direct costs are incurred for the benefit of a specific project.
- Indirect costs are incurred for the joint benefit of multiple projects and are applied through an allocation process.

[1] The winner's curse is a phenomenon that occurs in common-value auction. In such auctions it has been frequently observed that winner bidders tend to overbid due to imperfect estimates of value. This substantially reduces their winnings, often leading to losses rather than profits. As mentioned by Kagel and Levin (2002), "You win, you lose money, and you curse."

- Fixed costs occur regardless of the complexity of the project. An example of a fixed cost is plant maintenance.

- Variable costs vary in relationship to related activities within the project, such as raw materials.

Cost calculation allocates costs in accordance with the principle of cost causation, which means costs should be allocated to those services or products that cause those costs to arise. This requires the implementation of appropriate cost allocation methodologies. In large-scale plant engineering, a well-defined cost allocation system will enable at least 90 percent of the costs to be allocated on the basis of direct or indirect cost causation (Lock, 2004).

In large plant industry, project costs can be divided into two parts, i.e. above-the-line costs and below-the-line costs. The above-the-line costs contain the basic project costs including direct costs and indirect costs (overheads), while the below-the-line costs comprise various allowances. The items of these costs are presented in detail below (Lock, 2007).

<u>Above-the-line costs</u>
Costs that are directly attributable to a project activity are considered direct costs, such as direct labor, direct materials and direct expenses. They are also called the prime costs. The WBS is usually the starting point for estimating the direct costs. From the WBS, a detailed list of project activities is developed, so that the project cost estimate can be allocated to the various activities in the project WBS.

Indirect costs, also called overheads, are operating costs incurred for common or joint purposes. These costs, including fixed and variable overheads, are not easily adaptable to be charged directly to individual projects. Fixed overheads are stable costs that occur regardless of whether or not goods are being produced (e.g. rent of factory). Fixed costs are allocated based on machine hours. Variable overheads are costs that vary depending on the number of goods produced and therefore are allocated based on the number of labor hours (e.g. utilities).

Customers of large capital projects tend to be critical with respect to proposed overhead rates chargeable to their projects. They often ask for detailed itemizations for the proposed overhead costs. In fact, the overhead rate used for a large project is usually to be negotiated with the customer before an order can be won.

<u>Below-the-line costs</u>
Estimation work is prone to errors and omissions, so that it is necessary to have some cushions for those risks by adding some extra items below the line drawn under the basic project cost estimate. These can include allowances for cost escalation, exchange rate fluctuation and other contingency allowances. The following items are common below-the-line costs in project estimates:

Cost escalation
For large projects that are expected to take several years to complete, the contractor needs to include the costs of escalation in labor and materials costs over the project length. Cost escalation is often expressed at an annual rate percent. For example, for a three-year project the contractor anticipates a 4% wage increase in each of the last two years of the project. If the same project requires that the contractor purchases most of the materials during the third year, the current materials cost estimates may need to be increased by a certain percentage to cover the expected cost of the materials at the time they will be purchased (Sinnott, 2005; Gido and Clements, 1999).

Contingency allowances
Contingency is an amount the contractor may want to include to cover the unexpected items that could have been overlooked or tasks that have to be redone because they did not work the first time (Gido and Clements, 1999; Humphreys and Wellman, 1996). Estimating errors commonly result from the failure to appreciate additional costs from design errors, production mistakes, material or component failures and the like. The degree to which these contingencies are going to be added to the project costs depends on many factors, including the type of project, the general efficiency standard of the firm, the soundness of the engineering concepts and so on. For a straightforward project, not entailing an inordinate degree of risk, allowances are always very small and should never be set more than five percent of the above-the-line costs (Maynard and Zandin, 2001). The scope for adding an adequate contingency allowance is obviously limited if there is high price competition from the market. If the perceived risk requires a very high contingency allowance, perhaps the company should reconsider whether to bid at all. Therefore, it is important to involve the risk

assessment into the bid/no bid decision discussed in the project planning phase.

Currency fluctuations
Since most large-scale plant orders in Germany come from foreign countries, there is uncertainty risk, especially when exchange rates are volatile. Some mitigation of this effect can be achieved if the contract includes safeguards. Otherwise, it is a matter of skill, judgment and foresight. Common practice in project cost estimating is nominating one currency as the control currency for the project and then converting all estimated costs into that currency using carefully chosen exchange rates. Whether or not the contractor wishes to disclose the exchange rates used in reaching its final cost estimates, the rate used for all conversions must be shown clearly on the estimation documents (Smith, 1995).

Because of keen competition, safety factors in the shape of a high mark-up or for contingency allowances are rather small. In the short-term consideration, the lower limit of a bid price is estimated by costs directly caused by a project. Each bid price larger than this lower limit makes a contribution to cover the fixed costs and the safety factors (VDI, 1983). In the book *International bid preparation*, the authors Baldwin et al. (1999) assessed the data from the UK plant construction market during twenty years to identify the relative importance of the cost elements to make a clear set of conclusions for bidding:

- Within the calculated elements the largest is the direct cost. Therefore, every step must be taken to ensure that this is calculated with the greatest accuracy in order to minimize inaccuracy in the direct cost estimate.

- The profit and risk elements, although important in the bid equation, are much smaller than the direct cost element and are influenced by the subjective adjustment.

Therefore, the following chapters focus on direct costs to estimate the lower limit of the bid price.

3.4.2. Types and Accuracy of Estimates

Due to the high operating expense and low chance of success, for each inquiry or ITB it is important to adapt expense for bid estimating to its chance of success. The accuracy of the project cost estimate and the effort required to calculate it must be appropriate for the decision being made. There are different estimation methods with different levels of accuracy, among which most frequently applied are the ANSI standard from the American National Standards Institute and the AACE method from the American Association of Cost Engineers. In the following, both methods are described in detail.

ANSI Standard defines three types of cost estimates with increasing order of accuracy (ANSI Standard, 1989):

- Order of magnitude: An order-of-magnitude level of cost estimate is usually based on *preliminary statements* of requirements. This is done in the requirements definition stage when there is a preliminary listing of deliverables. The accuracy of order-of-magnitude is supposed to be -30% to $+50\%$. However, there is little control of accuracy, and this approach involves a very high level of inaccuracy.

- Budget: The budgetary level of a cost estimate is based on *system functional* requirements with at least preliminary deliverables, receivables, and schedules presented by subsystems. Budget estimates typically have an expected accuracy of -15% to $+30\%$. These estimates require knowledge of the site, flow sheet, equipment, and buildings. Also, rough specifications for items such as insulation and instrumentation are needed.

- Definitive: The definitive level of cost estimate is based on a *subsystem functional* design wherein the deliverables, receivables, and schedules are carefully defined. As stated in ANSI Standard Z94.2, a definitive estimate, i.e. an estimate with an expected accuracy of $+15\%$ to -5%, "…is an estimate prepared from very defined engineering data …(including) …as a minimum, fairly complete plot plans and elevations, piping and instrument diagrams, one line electrical diagrams, equipment data sheets and quotations, structural sketches, soil data and sketches of major foundations, building sketches and a complete set of specifications." In other words, the engineering of the project must be fairly well underway to permit a definitive estimate to be performed.

AACE International has proposed an expansion of the ANSI estimate classifications to five types with expected accuracy levels and provides a comparison of the estimate classification practices of various firms and organizations in Figure 3.4 (Christensen and Dysert, 2005):

- Class 5: Order of magnitude with an accuracy of ±40%
- Class 4: Study (factored) with an accuracy of ±30%
- Class 3: Preliminary (budget authorization) with an accuracy of ±20%
- Class 2: Definitive (project control) with an accuracy of ±10%
- Class 1: Detailed (firm or contractors) with an accuracy of ±5%.

INCREASING PROJECT DEFINITION

AACE Classification Standard	ANSI Standard Z94.0	AACE Pre-1972	Association of Cost Engineers (UK) ACostE	Norwegian Project Management Association (NFP)	American Society of Professional Estimators (ASPE)
Class 5	Order of Magnitude Estimate -30/+50	Order of Magnitude Estimate	Order of Magnitude Estimate Class IV -30/+30	Concession Estimate Exploration Estimate Feasibility Estimate	Level 1
Class 4	Budget Estimate -15/+30	Study Estimate	Study Estimate Class III -20/+20	Authorization Estimate	Level 2
Class 3		Preliminary Estimate	Budget Estimate Class II -10/+10	Master Control Estimate	Level 3
Class 2	Definitive Estimate -5/+15	Definitive Estimate	Definitive Estimate Class I -5/+5	Current Control Estimate	Level 4
Class 1		Detailed Estimate			Level 5 Level 6

Figure 3.4.: Comparison of classification practices (Christensen and Dysert, 2005)

The five classes from AACE provide guidelines for applying the principles of estimate classification specifically to project estimates for engineering, procurement, and construction work for the process industries (Christensen and Dysert, 2005). Therefore, we take the classification from AACE as reference to identify the accuracy of cost estimates.

In Figure 3.5 the five estimate classes are presented in relationship to the identified characteristics. The level of project definition is the primary characteristic and determines the estimate class. The other four characteristics are secondary characteristics that are generally correlated with the level of project definition. The characteristics are typical for the process industries but may vary from application to application (Christensen and Dysert, 2005).

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.
[b] If the range index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Figure 3.5.: Cost estimate classification matrix for the process industries (Christensen and Dysert, 2005)

Class 5 estimates are generally prepared based on very limited information and therefore have the inherent inaccuracies. The related effort e.g. to prepare for a USD 20 million project is between one and 200 hours, depending on the project and the estimating methodology used. This estimate class is used for any number of strategic business planning purposes, such as but not limited to project screening, project location studies, assessment of initial viability, evaluation of alternate schemes, evaluation of resource needs and budgeting, long range capital planning, etc. This class falls into the ANSI Order-of-magnitude estimate classification. The expected accuracy is -20% to -50% on the low side and +30% to +100% on the high side.

Class 4 estimates are generally prepared based on limited information and have an accuracy range of -15% to -30% on the low side, and +20% to +50% on the high side. Typically, engineering is from 1% to 15% complete and the efforts for a USD 20 million project are typically as little as 20 hours or less to perhaps more than 300 hours. This class of estimates is generally used for project screening, determination of feasibility, concept evaluation, and preliminary budget approval. This class falls into the ANSI budget estimate classification.

Class 3 estimates are generally prepared to form the basis for budget authorization, appropriation, and/or funding. Therefore, they typically form the initial control estimate with all actual costs and resources. Typically, engineering is from 10% to 40% complete and the related efforts to prepare for e.g. a USD 20 million. Projects are typically as little as 150 hours or less to perhaps more than 1,500 hours. Typical accuracy ranges for Class 3 estimates are -10% to -20% on the low side, and +10% to +30% on the high side. This class falls also into the ANSI budget estimate classification.

Class 2 estimates are generally prepared to form a detailed control baseline against which all project work is monitored in terms of cost and progress control. For contractors, class 2 estimates are often used as the bid estimate to establish contract value. Typically, engineering is from 30% to 70% complete. Typical accuracy ranges for Class 2 estimates are -5% to -15% on the low side, and +5% to +20% on the high side. This class falls into the ANSI definitive estimate category.

Class 1 estimates are generally prepared for discrete parts or sections of the total project rather than generating this level of detail for the entire project. The parts of the project estimated at this level of detail will typically be used to evaluate bid checking or to support contractor negotiations. Typically, engineering is complete from 50% to 100% and would comprise virtually all engineering and design documentation of the project and complete project execution and commissioning plans. Class 1 estimates require the most effort to create, which may involve efforts between 600 and 6,000 hours for a USD 20 million project. Class 1 is the most accurate estimate. The typical accuracy on the low side is -3% to -10%, and on the high side +3% to +15%. This class is also included in the ANSI definitive estimate category.

Through selection of the estimate classes, it is possible to adjust expense of bid generation to its chance of success. Class 5 can be used for non-binding inquiries, which requires less effort. We can use Class 4 or Class 3 for the bid/no-bid decision depending on the complexity of the project, Class 2 estimate for the bid preparation process, and Class 1 for the contract negotiation.

3.4.3. Representation of Cost Data

Different sources of data support cost estimates (Humphreys, 2004; Murphy, 2004):

1. Purchase orders,
2. Vendor quotes,
3. Similar project costs: costs of similar project, and costs of project components,
4. Proprietary cost data files: historical company costs, and in-house projects,
5. Published cost information.

It is often more convenient to use indices published for various industries in the trade journals, e.g. Journal Process Engineering for the chemical industry in the United Kingdom. A composite index for USA process plant industry is published monthly in the Journal Chemical Engineering, the Chemical Engineering plant cost index (CEPCI) (Sinnott, 2005). However, published information needs to be used carefully, because the accuracy level of such data is not known. Sometimes the basis for such data is not even indicated (e.g. whether purchased or installed costs are being presented). Installed cost figures also may or may not include auxiliary equipment, and some costs might be for entire plants while others may be for battery-limit installations only. Further, unless the published data is dated or includes a cost index value, it is often impossible to correct for inflation since the data was obtained. Unless the publication is very specific about exactly what is included in the cost figures and about the data of the information, the published data should not be used (Humphreys, 2004).

3.4.4. Estimating Techniques

For each estimate class there is a typical estimating method to apply. In the following an overview of the estimating techniques is provided.

Cost-Capacity Estimate (Chilton, 1950)
An approach of cost estimate for pre-feasibility studies is cost-capacity curves and factors. In 1950 Chilton published comprehensive information and data on cost versus capacity. He provided data on some 35 complete plants, which he presented as straight lines on log-log paper. Their slopes ranged from 0.33 to 1.02, but the bulk of them were close to 0.6 and their overall average was also close to 0.6, which is known as the “6-10th’s rule” (Chilton, 1950). The capital cost of the present plant is determined by the ratio method. The price of the previous plant project is adjusted for size (capacity) by using the 6-10th’s rule. In formula form, it is

$$C_2 = C_1(V_2/V_1)^{0.6}$$

where C_2 is the capital cost of a plant of capacity V_2 and C_1 is the capital cost of a plant of capacity V_1 .

The above-mentioned Class 5 may refer to this method to make a rough estimate.

Factorial Estimate
The preliminary capital cost estimate is prepared using *factorial estimate*, also

called module estimating. In such a case, total cost is developed from a module: a cost entity. The estimating technique proposed by Lang (1947), known as Lang Factor, uses the total estimated cost of the plant and equipment as the module to which a factor is then applied to derive the total estimated cost. The basis for factorial estimate is the observation that the costs of component parts of process plants bear similar ratios to each other in different plants. Consider the breakdown of the plant cost into the following components (all components include the associated site construction and painting costs) (Watermeyer, 2002):

- civil works
- structural steelwork
- mechanical equipment
- electrical equipment and reticulation
- instrumentation and control gear
- piping
- transport to site
- indirect costs (engineering and management, insurance etc.).

The largest of these components is invariably the mechanical equipment, and it is also the most fundamental component. The other plant components follow from the mechanical equipment needs. So in the simplest factorization technique, the plant cost is factorized from the mechanical equipment cost, which is generally in the range of 30-45% of the direct field cost, or 25-40% of total cost.

Factorize the total mechanical equipment costs to the all-in project cost:

- Total Field Cost = 2.0 to 2.6 x Mechanical Equipment Cost
- Total Project Cost = 1.6 to 1.8 x Total Field Cost

The accuracy of factorization techniques depends on the similarity of the type of plant, and also the consistent grouping of cost elements into the factorized components. The advantage of the quantity ratio method is that the location of the project is less of a problem. Depending on the location, the quantities can be multiplied with unit material costs and erection/field man hour productivity ratios applicable for that specific location.

For most clients and circumstances, before the project is authorized, the plant is designed and the costs are listed in detail. Therefore, factorization estimating methods are usually restricted to pre-feasibility work or comparison of plant alternatives.

Class 4 estimates virtually always use stochastic estimating methods such as equipment factors.

Class 3 estimates usually involve more deterministic estimating methods than stochastic methods. They usually involve a high degree of unit cost line items, although these may be at an assembly level of detail rather than individual components. Factorization may be used to estimate less-significant areas of the project.

Detailed Estimate (Ellsworth, 2007)
The detailed estimate (or contractor's estimate) is based on complete engineering drawings, specifications, and site surveys. Fixed and firm prices against complete specifications are obtained from vendors for all equipments. All Bills of Materials are complete and accurate and are priced by erection contractors. In spite of this level of detail, the probable error in the estimate is still $\pm 5\%$.

For detailed estimate the estimating team requires the following general and engineering information:

- copies of all inquiry documents,
- finalized P&IDs for process, utilities and offsite utilities,
- detailed plot plans,
- detailed engineering specifications,
- detailed planning schedules for engineering, planning, procurement, construction,

- equipment data sheets,
- detailed engineering data for all disciplines (civil/piping/electrics/etc.),
- local site conditions/labor availability,
- quotations for all equipment items.

Class 2 estimates always use the detailed estimate method. Class 2 estimates are prepared in great detail, and often involve tens of thousands of unit cost line items. For those areas of the project still undefined, an assumed level of detail takeoff (forced detail) may be developed to use as line items in the estimate instead of relying on factoring methods.

Class 1 estimates involve the highest degree of deterministic estimating methods, and require a great amount of effort. Class 1 estimates are prepared in great detail, and thus are usually performed on the most important or critical areas of the project. All items in the estimate are usually unit cost line items based on actual design quantities.

3.4.5. Automation of Estimation

The development of computer-assisted estimating systems began in the late 1960s (Orr et al., 1978). Early efforts included a study of the use of computers in the handling, storage, retrieval and sorting of data. This provided a data base which could be used in an estimating program that developed erected cost from basic plant and equipment design data. A wide variety of programs is now available as an excellent tool to speed up calculations. Whilst the computer can be a very valuable and powerful tool, it cannot think or make reasoned judgments, which every new situation demands, and its ability to decide is limited. Unfortunately, every capital estimate, particularly in the process industries, is in effect a "new situation", every plant, and hence every estimate, is unique. Accuracy was, and still is, dependent upon the technique and the data used in the program, as well as the reliability, completeness and correctness of the input (Kharbanda and Stallworthy, 1988). Software programs for cost estimates available on the market are mostly configuration software, which may accelerate the calculation, but not really support decision-making. They are discussed in detail in the next chapter.

3.5. Project Scheduling

A WBS breaks large units of work into smaller activities. These smaller activities are used as the basis for the project schedule. A project schedule is a road map of a project that states the duration and sequence of activities. In order to develop the project schedule, there are some elements to be considered (Kolisch, 1995):

- Activities: Activity attributes describe the who, what, where, and how of the project activities to be completed. This information is to group and categorize activities in the schedule. It is important to distinguish activities from schedule events. An event is usually one specific point in time, while an activity is performed over a period of time.
- Duration: The activity duration is defined as the time required to complete the work involved in a specific activity. An activity duration estimate must be based on the quantity of resources expected to be used on the activity. The estimate should be realistic.
- Precedence relations: Due to technological restrictions, some activities have to be accomplished before others can start. A project network diagram is a schematic display of the dependencies among project activities. These relationships are represented graphically in an activity-on-node (AON) network diagram, where an activity is represented by a node and the precedence relationship between two activities is represented by a directed arc [2] (Kolisch et al., 1992).
- Resource: Activity resource requirements specify type and amount of resource needed.

There is a distinctive difference between projects with respect to the certainty of these elements. Some projects consist of probabilistic elements, while some

[2] Besides the AON representation precedence relation can be depicted by the activity-on-arc representation, which is not considered here.

projects are made up of deterministic elements. Depending on the deterministic or stochastic elements, a project schedule can be represented in different ways (Kolisch et al., 1992).

The Critical Path Method (CPM) was developed by Kelley (1961) as a network model for project management. CPM assumes deterministic activity durations and precedence relations between the activities. Within CPM, the project is regarded as entirely deterministic.

The Program Evaluation and Review Technique (PERT) is a network model that allows for randomness in activity completion time. This method extends CPM by considering the uncertainty in estimating activity duration in order to estimate the probability of finishing a project in a given time. PERT (Malcolm et al. 1959) was developed to efficiently plan and produce the U.S. Navy's Polaris missile system subject to probabilistic durations of activities. PERT originally was an activity-on-arc network, in which the activities are represented on the lines and the milestones on the nodes. Over time, some people began to use PERT as an activity-on-node network. In the Graphical Evaluation and Review Technique also the precedence relations are probabilistic (Pritsker and Happ, 1966).

Since the duration estimation is deterministic in this work, in the following we use CPM to construct the project network diagram. A project network diagram consists of a series of project activities arranged in a logical flow. It is the basis for a project schedule and provides a consistent framework for planning, monitoring, and controlling the project. Every work element from the WBS is represented in the network diagram, and only WBS work elements are represented there. The WBS contains all of the activities necessary to complete a project, but it is not a scheduling tool. The project network diagram is a scheduling tool that shows the predecessor and successor relationships between activities from the WBS. In the project network diagram:

- there are dummy start and end nodes
- activities from WBS are represented by nodes
- the precedence relations are represented by arcs. There are three types of precedence relations, namely finish-to-start, finish-to-finish, and start-

to-start. The finish-to-start relationship is the most common precedence relationship. In a finish-to-start relationship, an activity can start only if all its predecessors are finished.

Given an estimated duration for each activity in the network diagram and using the project's estimated start time and the required completion date as a reference, the following time for each activity can be calculated (Gido and Clements, 1999).

- Earliest start time (EST): It is the earliest time at which an activity can begin, which is calculated based on the project's estimated start time and duration for preceding activities.

- Earliest finish time (EFT): It is the earliest time by which an activity can be completed, calculated by adding the activity's duration estimate to the activity's earliest start time.

- Latest start time (LST): It is the latest time by which an activity must be started, calculated by subtracting the activity's duration from the activity's latest finish time.

- Latest finish time (LFT): It is the latest time by which an activity must be completed, calculated based on the project's required completion time and duration estimation of succeeding activities.

The EST and EFT are determined by using the forward recursion method, that is, by working through the network diagram from the beginning of the project to the end of the project. The LFT and LST time are determined by using the backward recursion method, that is, working through the network diagram from the end of the project to the beginning of the project.

The algorithms to get the EST and EFT are presented in Algorithm 1 and for the LST and LFT in Algorithm 2.

The difference between the pairs of start and finish time for each activity is the *slack time* for the activity. Slack is the amount of time that an activity can be delayed without delaying the project completion date. When all the earliest possible and latest permissible time have been added to the network diagram, there will be a path called *critical path*, where the earliest and latest time are the

Algorithm 1 Forward recursion

Initialization : EST_1 = EFT_1:=0 ;
for $j := 2$ to J **do**
  EST_j:= max { $EFT_i \mid i \in P_j$ } ;
  EFT_j:= $EST_j + d_j$;
end for
Stop: An earliest start and finish time has been calculated for every activity.

Algorithm 2 Backward recursion

Initialization : LFT_J = LFT_J:= T ;
for $j := J-1$ down to 1 **do**
  LFT_j:= min { $LST_i \mid i \in S_j$ } ;
  LST_j:= $LFT_j - d_j$;
end for
Stop: A latest start and finish time has been calculated for every activity.

same, indicating zero slack.

A critical path presents the longest path in the overall network diagram and determines the actual project completion time. Activities on the path are critical activities that must claim priority for resources and for management attention (Lock, 2007). In summary, the critical path is:

- the longest path through the project
- the path with zero slack time
- the shortest time to complete the project.

After obtaining the outline of the schedule, the next step is to allocate the resources to activities to assure that the required resources do not exceed the available ones.

According to Blazewicz et al. (1983), resources are classified along the following lines: categories, types and numbers. There are three categories of resource: renewable, nonrenewable and doubly constrained.

- Renewable resources are available for every single period (e.g. day, week, month) regardless of the project length. E.g. manpower and machines are renewable resources.

- Nonrenewable resources are only limited within the total duration of a project. No limitation of consumption is given within one period. A typical nonrenewable resource is the project budget.

- Doubly constrained resources are limited on a period basis as well as on a project basis. Formally, each doubly constrained resource can be represented by one renewable and one nonrenewable resource, respectively (Talbot, 1982), so that doubly constrained resources are normally not considered.

Each category can be distinguished in different types, e.g. machines with divers functions or different productivity. Finally, the number of resources within each type is different.

An activity is processed with resources in one or several modes. Each mode represents a different way to perform the activity under consideration, e.g. an activity can be performed with 2 workers in 3 weeks, or with 3 workers in 2 weeks. Associated with each mode the duration of an activity is determined in the number of periods. Switching from one mode to another mode can make changes of the duration (time-resource trade-off). According to the mode used, resource-constrained project scheduling problem (RCPSP) can be distinguished between single-mode resource-constrained project scheduling problem (SMRCPSP) and multi-mode resource-constrained project scheduling problem (MMRCPSP) (Kolisch, 1995). In the SMRCPSP, a project can be performed in one mode only, whereas in the MMRCPSP a set of allowable execution modes can be specified for the activity's execution. Each mode is characterized by a processing time and amount of a particular resource type for completing the activity. In our case a component of a large-scale plant can be produced in different countries representing different modes. The way to procure/produce and transport a component varies in different countries, due to the following reasons:

- Market and supplier situations affecting the procurement time of components, which may vary in different countries

- Different skills and know-how of workers resulting in different production time of a component

- The distances for transportation of a component change in countries leading to different transportation time

Since the classical SMRCPSP is exclusively concerned with the minimization of the makespan of a project, nonrenewable resources are not relevant any more and therefore are not considered. The SMRCPSP is a generalization of the classical static job shop problem and many other scheduling problems, e.g. a variety of single and parallel machine problems (Baker, 1974) as well as an open shop problem (Sprecher et al., 1995).

The MMRCPSP has the great benefit of representing different ways to perform an activity. The different modes enlarge the solution space leading possibly to a better solution. However, the problem becomes much more difficult. In fact, MMRCPSP is one of the most general and most difficult project scheduling problems and belongs to the class of the NP-hard problems (Blazewicz et al., 1983).

More details of SMRCPSP and MMRCPSP relating to model formulation and solution methods are introduced in the following chapters.

4. Challenge and Response

In Chapter 3, project management methods are illustrated to deal with the complexity of a large-scale plant. Due to the international nature of the plant business and the intensive competition in the international market, management of a plant project becomes much more complex. In Section 4.1 the current situation of the German plant industry is introduced. Plant demand in the global market falls dramatically due to the economic downturn. Plant manufacturers suffer from ongoing recession. Limited plant orders intensify competition. Plant manufacturers have to face hard challenges, i.e. huge pricing pressure, shorter project duration, strict local content rules, and new requirements on the bid generation, which are described in Section 4.2. The response to challenges in the bid generation is illustrated in a case study in Section 4.3. However, the integrated decision of location choice by global sourcing and project scheduling is not considered. Therefore, in Section 4.4 the interaction of location choice and project scheduling in the bid generation is clarified.

4.1. Current Market Situation of the German Plant Industry

As mentioned in Section 2.2, German plant sales depend generally on the demand in foreign countries. The economic slowdown since mid-2008 has affected the demand of industry plants significantly (Gottwald et al., 2009):

- The largest sales slump in the steel industry for 40 years results in a sharp market slowdown in the sector of steelworks and rolling mills, which identifies the end of the boom since 2003.

- Ongoing chemical plant projects have been interrupted and the award of new projects has been delayed. This trend is reflected particularly in the falling orders from Middle East and South America. In both regions, the interrupted projects have increased by 94% and 84% in 2008 compared to 2007. Investors relying on external financing have frequently not received any funding with reasonable conditions for their projects. Moreover, the reduced oil and gas prices had an adverse effect on the budgets of raw material nations; the economic feasibility of projects has deteriorated.

- In the economy-sensible sectors such as metal, oil and gas industry the orders of electrical equipments fall off. Furthermore, the amount of large orders sinks. In 2007 18 large orders with the value of 1.3 billion Euro were awarded, while there were only 15 orders with 876 million Euro in 2008.

- Air and gas liquefaction plants have suffered a considerable decline since the end of 2008. Especially clients from steel industry, which needs a large amount of gas for its production processes, have broken or even canceled their orders.

The market situation becomes much worse in 2009. The demand for plants declines significantly in response to the worldwide economic slowdown, e.g. a reversal rate of around a third is to be expected in the chemical plant sector according to prognoses of the Large Industrial Plant Manufacturer's Group (Gottwald et al., 2009).

4.2. Challenges in the Global Plant Market

The economic downturn intensifies the competition in the international plant sales. On the one hand, clients speculate for falling plant prices. On the other hand, a large number of plant suppliers compete for a limited number of orders and attempt to acquire orders by providing lower prices, which leads to high pricing pressure.

In the international market, a plant constructor has to face more competitors than in his domestic market. The main competitors of German plant constructors come from the USA, Japan and Western Europe (Italy, France and Scandinavian countries) (Gottwald et al., 2009). Many newcomers from the developing countries supply plants with high quality through developing technology with efforts as well as by means of acquired know-how, which is transferred from previous projects performed by experienced high-tech plant constructors. Since the operating costs in developing countries are typically lower than those in the developed countries, newcomers from these countries offer considerably competitive prices. In addition, supports of their countries, e.g. advantageous taxation politics, financial support, and export credit insurance, provide those newcomers with additional competitive edge. In the last years, China has become a new competitor especially for power plants, cement plants and plants in the synthetics industry. In 2006, China ranked the fifth place in machinery export, for the first time ahead of the United Kingdom and France (Gottwald et al., 2007).

Due to the good reputation in machinery and plant construction, Germany remains the market leader in this industry. However, high operating costs, especially Euro's appreciation against the dollar, have negatively impacted German plant constructor's export. According to VDMA, one percent of Euro appreciation cuts machinery makers' sales by one percent. In addition, in order to realize quick amortization of their investment and reduce financial risks, plant customers require shorter project durations, which are harder to fulfill. According to VDMA, about 30-50% time reduction has been realized, but a further improvement is expected (Gottwald et al., 2008). Since the plant market is shifted from the seller market to the buyer market, one would need to meet the buyer's short completion time requirement to win a contract.

The German plant manufacturers are permanently stipulated to involve the foreign deliveries and local services in their projects and the scope of financing to allow for the international cooperation. As a result, the share of the German domestic deliveries and services for the international orders falls continually. In the 80s, the domestic share was 75% and in the 90s it was still 72%. However, in 2008 it fell to only 55% (Gottwald et al., 2009). This trend will continue not only because of the internalization of the value creation process, but also due to the global latent protectionism intensified by the global economic downturn.

Protectionism in form of local content rules is regulated by law or required by clients. However, costs and quality as arguments play also an important role in consideration of local content regulations.

In the following section an introduction of local content regulations is given in detail.

4.2.1. Local Content Requirement

Lots of plant orders coming from foreign countries typically need to satisfy a so-called Local Content Requirement (LCR). A LCR is a regulation that requires that some specified fraction of a final good be produced domestically (Krugman and Obstfeld, 2008). *Local* in the term of LCR means within the national territory of the customer's country. *Local content* is usually defined in volume or value terms. A *physical content* requires a certain fraction of the total quantity of components or raw materials used to produce the final good to be of domestic origin (Munson and Rosenblatt, 1997). A *value-based content* requires the value of locally manufactured components to be at least as large as a specified percentage of the final good's value. While a physical scheme tends to be used when the final and intermediate goods are relatively homogeneous (e.g. tobacco in Australia), heterogeneity (e.g. automobiles) almost demands a value-based scheme, because a physical scheme might encourage the use of domestic suppliers for simple items while leaving expensive high-tech items for the foreign suppliers (Munson and Rosenblatt, 1997). In this dissertation we focus on the value-based scheme, since large-scale plants are heterogeneous.

LCR is hence defined as the requirement that a fixed percentage of the output of a given industrial product is composed of input with a local origin (UNIDO, 1986). The LCR can be set by government or by private industry. Government attempts to establish local content rules for various reasons: saving foreign reserves, enhancing technology elements of production, stimulating the spirit of entrepreneurship, and improving skill level of the labor force, as well as expanding the role of small- and medium-size enterprises in the industrial development of the country (Günter, 1985). Since LCR can make an important contribution to the expansion of the capital goods industry, developing countries are trying to employ local contents as an important policy to enter into or expand production in the capital goods industry, to facilitate the subsequent export of these parts and components. Private industry may desire to reduce costs by involving local vendors and avoiding import duties by giving local content (Günter, 1985).

An inducement of LCR could take the form of the right to import intermediate goods duty free. In the case of failure to meet the requirement a high penalty tariff rate on all intermediate imports are commonly imposed (Grossman, 1981). 83 percent of private sector respondents in a U.S. Commerce Department survey replied that local content rules had great effect or some effect on their industry (Lion, 1994). “But achieving global economies of scale and efficiencies through international sourcing may be incompatible with developing high proportions of local content in all countries”(Vickery, 1993).

The LCR has increased rapidly in recent years. In some important customer countries such as China, Egypt and Iran, the LCR reaches and sometimes even exceeds 50 percent of the total plant value. Table 4.1 illustrates the increase of LCR for urban rail projects in China undertaken from 1994 to 2005 by Rail Automation Braunschweig, a division of the company Siemens Transportation Systems. Over the last ten years the length of urban rail per month has increased continually. At the same time the requirement of domestic value added in China has increased dramatically.

PROJECT	A	B	C	D	E	F	G
Duration in month	55	35	36	23	31	36	64
Length in km	19	30	23	17	20	39	69
km / month	0.34	0.86	0.64	0.73	0.64	1.08	1.08
LCR in %	0	0	55	57	52	52	80

Table 4.1.: Projects from Siemens Transportation, division Rail Automation in China

A high LCR limits the use of global sourcing in other countries and may cause a drain of know-how of manufacturers.

4.2.2. New Requirements on Bids

The intensification of the international competition results in new requirements in the bidding phase:

- The number of the submitted bids increases. Since more plant constructors are competing in the international environment, the easiest way for clients to get market transparency is via mass inquires resulting in more bids.
- The uncertainty and risks increase due to the lack of detailed and precise information of the foreign markets and competitors' behavior, which makes it more complex to determine a bid price. Global procurement of components also makes estimating project time more challenging.
- The scope of requirements on a detailed solution increases, which may cause drain of know-how.
- The scope of work extends. More free services are demanded along with the project's deliverable in the bidding phase. A direct result is that time and cost for bid generation increase.
- While the effort for bid generation grows, the success rate of bids drops.

Facing the new challenges in the fierce competition, plant constructors are striving to make improvements in the bid generation:

- Optimizing the cost to keep a reasonable low bid price;
- Improving the accuracy of cost and time estimation;
- Reducing the cost and time for bid generation.

In order to come up with a low bid price that will stand out from the hard competition, plant constructors attempt to reduce costs through global sourcing, especially in low-wage countries. They typically establish foreign factories to get benefit from tariff and trade concessions, cheap labor, capital subsidies, and reduced logistics costs in foreign markets (Ferdows, 1997). However, global geographical distance not only elevates transportation costs but also prolongs production time due to inadequate worker skills, infrastructural deficiencies, supplier unavailability, and quality problems (Meixell and Gargeya, 2005). Additionally, global sourcing carries risks of variability and uncertainty in currency exchange rates. Exchange rates affect the price for goods that are purchased in the supplier's currency, and so influence the timing and volume of purchases as well as the financial performance (Meixell and Gargeya, 2005). Furthermore, non-tariff trade barriers are to be considered, e.g., LCR restricts the scale of global sourcing and may cause a forced technology transfer. Therefore, international plant constructors must decide which components to be procured locally to satisfy local content rules and which components to be imported to get some of the advantages of global sourcing.

Miscalculation of costs can result in profit reduction or failure in the bidding process. Due to global sourcing, production/procurement costs and transportation costs in different countries must be considered to make an accurate estimate. Not only the costs but also the production/procurement and transportation durations may vary in different countries, which may result in different project completion time. To get an accurate and low bid price, costs and time should receive an integrated consideration.

Reducing cost and time for bid generation as well as enhancing the flexibility of bids can be supported by systematization of the bid generation in the bidding phase and through different scenario analysis in the negotiation phase. Software supporting the bid generation do not provide support for the location decision, which affects both plant costs and project duration. This deficiency is demonstrated in the following business case.

4.3. Case Study

The Swiss group Bühler is the world's largest know-how center for grain processing. About 65 percent of the total global grain production is processed by Bühler plant systems. Our cooperation partner, the subsidiary Bühler Braunschweig, Germany, engineers and constructs brewing and malting plants throughout the world. Besides the production site in Braunschweig, Bühler runs main sites in

Switzerland, China, India, Spain, South Africa and the USA.

As common in plant engineering, Bühler uses the configuration software *Navigator* from EAS Engineering Automation Systems Ltd. to support product configuration, bid generation and price calculation. This software contains a Configuration Editor, a Bill of Quantity Editor and a Document Generator (EAS Engineering Automation Systems GmbH, 2009).

In the Configuration Editor the following project data are edited to support configuration of product variants and the setup of multi-layered service scopes, e.g. from the overall plant through to modules, components or services etc.:

- Product data describing requirements;
- Bills of Quantity with calculation parameters like weights, hours, costs, etc.;
- Item lists, scope of supply, split-up;
- Generation of contract specifications.

Using the Configuration Editor, projects can be engineered quickly by re-using previous project engineering data. A product structure is configured by retrieving and adapting available project data. The configuration is then carried out on the basis of the projected knowledge of logical relationships.

The Bills of Quantity Editor is a tool for working with quantities, weights, materials specifications, reference project specifications and other properties. The Bill of Quantity Editor is displayed in the form of tabular spread-sheets. It helps to process real project data in various views such as Bill of Quantity, pricing, contracts and services. The bid calculation is generated based on Bill of Quantity.

The Document Generator supports the automatic creation of consistent output documents of all kinds, such as bids, technical reports, calculation sheets, and technical specifications.

Since this software does not support the scheduling, it usually takes several hours to check constraints and construct schedules. Due to the worldwide production sites of Bühler, components of a plant can be produced in different countries with different costs and time. In the configuration software the production location for each component is determined either from experience or by operational rules. However, neither an optimization of costs is carried out nor production constraints are considered. Moreover, for each configuration the project schedule has to be verified manually with a significant manpower effort. Mr. Norbert Heide, senior project engineer at Bühler Braunschweig, stressed, "In view of the large number of plant components, some of which being very complex, it is mandatory to have a decision support software."

Therefore, the objective of this research is to develop an approach supporting cost optimization and accurate estimation of the lower limit of the bid price.

To achieve this objective, firstly, the following decisions need to be made:

- Which component is to be produced in which country, so that the LCR can be met, and drain of know-how can be avoided? It deals with the international facility location problem.
- And at what time can it be done, so that the project deadline can be kept? It deals with the resource-constrained project scheduling problem.

Both decisions interact with each other and should be integrated in the bidding phase to determine the minimal cost as the lower limit for the bid price.

4.4. Interaction of Location Choice and Project Scheduling

In order to integrate both decisions in the bidding phase, it is necessary to find out, how the decisions affect each other. First we make the following assumptions:

- Quantity and type of the plant components are described in a bill of materials.
- Each activity in the project network diagram represents the production or procurement of a component.

- For each component the decision of make-or-buy is already made. We concern only where, i.e. in which country, a component is made/bought[1].
- Precedence relations of activities are known from the technical specifications.
- The production or procurement costs of the components are estimated from purchase orders, vendor quotes, cost or pricing data of subcontractors, completed projects, escalation rates, construction unit rates, or published cost information (Murphy, 2004).
- Transportation costs for components can be estimated using indicators, such as freight rates (e.g. Baltic Dry Freight Index), tanker rates and other transportation tariffs.
- The duration of each activity can be estimated from experience resulting from completed projects, similar projects or delivery time from subcontractors or vendors.
- The project due date is demanded by the customer.
- An LCR is given by the customer.

For cost and time estimation in the bid generation we form two subproblems from this data: The location problem determines the production or procurement country for each component, whereas the project scheduling problem determines the production/procurement and transportation schedule (see Figure 4.1).

Since the production or procurement costs of components (K in Figure 4.1) as well as the associated transportation costs depend on the choice of location (C in Figure 4.1), the components are assigned to countries so that the total costs are minimized. The given LCR presents a constraint to the assignment of production/procurement countries.

An assignment also determines the production/procurement duration and transport duration of each component. With the data input of durations and with

[1] We do not consider the make-or-buy explicitly, but we can integrate the make-or-buy decision easily by viewing the procurement as a production mode to be carried out in a certain country.

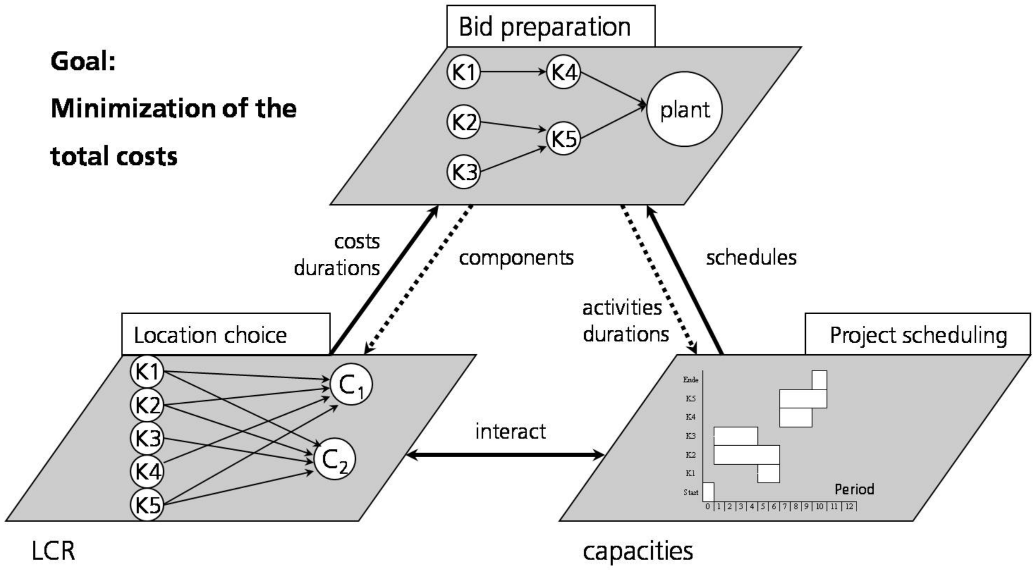


Figure 4.1.: Interaction of location choice problem and project scheduling problem

the described precedence relations among activities the subproblem of project scheduling is solved to determine the prospective completion time of the project.

Obviously, both subproblems interact with each other through durations. The choice of location determines the time needed to produce/procure and transport a component. In this way, the location decision affects the duration of the entire project. In turn, in case of a prescribed project due date, the time constrained schedule will affect the choice of locations, so that shorter production durations will be favored.

To obtain an accurate estimation of cost and time for bids, the above-mentioned interaction should be taken into account. However, such an integration is still missing in current practice.

Therefore, in the following chapters we focus on methods to integrate both decisions of location choice and project scheduling to minimize plant costs under complex constraints such as the given project due date, LCR and resources.

Part II.

Methodology

5. Mathematical Modeling

As mentioned in Part 1, usually the lowest bid wins the contract, therefore, a plant manufacturer aims at minimizing plant costs to get the lower limit of the bid price. Due to the international nature of the plant business and the requirement of local content, plant costs are affected by the location choice. Locations with lower costs are preferred to reduce the total costs. However, to meet the given project due date, the time constrained schedule affects the location choice, so that locations with shorter durations are favored. In consideration of this interaction, a trade-off between cost and time has to be made. To get a reasonable low bid price, plant costs need to be minimized. At the same time, constraints such as the given project due date, know-how protection, and resource availability are considered. For this purpose, the relevant literature in the related areas is reviewed: the global network design problem and the resource-constrained project scheduling problem. On the basis of analyzing models in both areas, we propose a mathematical optimization model, which minimizes the total plant costs in consideration of complex constraints in both location choice and project scheduling.

5.1. Literature Review

To integrate the location choice and project scheduling, this section aims to establish the state of current research in models for the international facility location problem and the resource-constrained project scheduling problem. Through a structured literature review, factors that are essential to the consideration of the location decision and scheduling problem are identified for the modeling in next section.

5.1.1. International Facility Location Problem

The location decisions are of great importance to a company, since they represent the basic strategy for accessing customer markets, and have a considerable impact on revenue, cost, and level of services. These decisions are always determined by an optimization procedure, which considers production costs, taxes, duties and duty drawback, tariffs, local content, distribution costs, and production limitations. The global location decision problem has received a significant attention in the research literature. There is a large variety of decision support models and corresponding solution algorithms for the strategic global network design. In this review, we focus on the model-based literature that addresses the global network design problem. The network design methods provide models for strategic decisions to determine the location of production, stocking, and sourcing facilities, and paths the products take through them. Such methods tend to be large scale, and to be used generally at the inception of the supply chain (Ganeshan and Harrison, 1995).

One of the earliest works in this area was found by Geoffrion and Graves (1974). They introduced a multi-commodity logistics network design model to optimize annualized finished product flows from plants to the distribution centers to the final customers.

Breitman and Lucas (1987) described the PLANETS model at General Motors to evaluate complex quantifiable business decisions, that is, to decide what product to produce, when, where and how to produce it, which markets to pursue and what resources to use. PLANETS was reported to be capable of providing optimal solutions for multi-period international location problems given pre-specified scenarios. Breitman and Lucas considered many features concerned with global supply chains in their model, including tariffs, local content, balance of trade, and trade complementation.

Cohen and Lee (1989) developed a normative model for resource deployment in a global manufacturing and distribution network. The objective maximized total global after-tax profit (profit - local taxes) through the design of facility network and control of material flows within the network. The cost structure consists of variable and fixed costs for material procurement, production, distribution and transportation. The decisions and associated costs occur in a single yet sufficiently long time period.

Cohen et al. (1989) presented a multi-period global supply chain model to assist in making the manufacturing decisions concerning global production and sourcing. The decision variables include the choice of supplier, the production quantity at each plant, and the amount of product for each market. The objective function maximizes after-tax profits in consideration of material flow constraints, plant capacity, market penetration strategies and local content rules.

Arntzen et al. (1995) provided a comprehensive mixed integer program to solve the global supply chain design problem at the Digital Equipment Corporation. The objective function minimizes fixed and variable production costs, inventory costs, transportation costs, taxes, and duties with consideration of local content rules, offset trade, and duty drawback. The decision variables in the model are location choice and production, inventory and shipping quantities. Time elements include manufacturing lead time and transit time. Time is measured as the number of days needed for production and for transit on each link in the supply chain, weighted by the number of units processed or shipped on the link. Thus, the overall response time of the supply chain is minimized as an alternative objective. The model is highly integrative, since it linkes multiple supply tiers by the bill of material, and solves for the optimal solution over both production and distribution segments of the supply chain. In fact, the objective function may be a weighted combination of cost and time so that either measure or both can be used to derive recommendations (Meixell and Gargeya, 2005).

Munson and Rosenblatt (1997) investigated a global supply chain problem with focus on local content rules in global sourcing. The mixed integer program selects suppliers and final production sites, and allocates purchase quantities for a particular market to minimize the sum of purchasing, production, transportation, and fixed costs of opening and operating a plant in a specific country. They consider provisions in the model for a bill of material, local content, and supplier capacity constraints.

Vidal and Goetschalckx (2001) developed a model for the global supply chain management problem with transfer pricing and transportation cost allocation.

This model simultaneously selects facility locations, computed flows between facilities, set transfer prices, and allocated transportation costs to either the shipper or the receiver to maximize after-tax profits across multiple tiers in the supply chain.

Although the location decision problem domain has already been addressed by many authors, a deficiency with respect to an investigation of large-scale industrial plant engineering was noticed by Meixell and Gargeya (2005). Regarding to the general aspects of the location decision discussed in the above-mentioned literature, we identify basic features to support decision-making in the bidding phase for large-scale plant projects. To provide the lower limit of the bid price, we minimize plant costs, which consist of production or procurement costs of components, and transportation costs. A component can be produced/procured only in one country. The transportation cost is that of the transportation from where a component was produced/procured to where it is needed. The given LCR as constraint is considered.

5.1.2. Resource-Constrained Project Scheduling Problem

Literature relating to the resource-constrained project scheduling problem is rich. We focus on the basic model formulation. For the zero-one programming model of SMRCPSP we refer to Patterson and Huber (1974), Patterson and Roth (1976), and Kolisch (1995). The objective is to minimize the completion time of the project subject to keeping each activity within the assigned time window, precedence relationship and resource constraints. Solution methods of SMRCPSP can be found in Davis (1966), Herroelen (1972), and Domschke and Drexl (2007). For MMRCPSP Talbot (1982) developed a model, which minimizes also the makespan of a project. Constraints such as each activity assigned exactly with one mode and completed within its time window, precedence relationship constraints, renewable and nonrenewable constraints are taken into account. For further research in the MMRCPSP field we refer to Talbot (1982), Kolisch (1995), Sprecher and Drexl (1998), Hartmann (1999), Heilmann (2003), Neumann et al. (2003), and Damak et al. (2009). Since a component of a large-scale plant can be produced/procured in different countries representing different modes, models of MMRCPSP are of great significance for this work. However, there are three main differences between this work and the standard MMRCPSP discussed by Neumann et al. (2003):

1. Neumann et al. (2003) view nonrenewable resources as special cumulative resources that are depleted over time but never replenished. For nonrenewable resources, resource-feasibility solely depends on the selection of activity modes and not on the schedule. Therefore, nonrenewable resources can be omitted when dealing with SMRCPSP. In this work, a mode relates to production or procurement of a component in a country. Resources in a country (mode) are independent of that in other countries (modes). Therefore, nonrenewable resources are not considered in this work.

2. In the standard MMRCPSP, modes may compete for renewable resources. In our case, resources are dedicated to countries, thus a usage of the same resource by different modes does not occur.

3. Neumann et al. (2003) model start-to-start relationships among activities in the MMRCPSP and hence define time lags between starting times of two activities. In this work, we differentiate between production and transportation times. The production time solely depends on the country chosen, whereas the transportation time depends on the country of production as well as the country of production of the successor activity. Moreover, production consumes renewable resources while transportation does not. In order to incorporate this feature, we adopt the formulation of Kolisch (1995) using finish-to-start relationships between activities.

Besides these differences, a quantitative decision support regarding the interdependencies between location choice and project scheduling for large-scale plant projects is still missing. Therefore, in the next section we propose a mathematical model to integrate both location choice and project scheduling problems in consideration of aspects discussed in the literature review.

5.2. Model Formulation

To integrate the above-mentioned decisions, a mixed-integer programming (MIP) model is proposed, which combines the model of the international facility location problem and the model of MMRCPSP to reach a solution in consideration of constraints such as the local content requirement, capacities and the project due date. The objective is to minimize the plant cost in order to estimate the lower limit for the bid price. This section starts with the introduction of the parameters, followed by formulation and discussion of the optimization model.

Parameters of the MIP formulation are set as follows:

- Parameter for the choice of locations:

J	Number of activities / components j ($j = 1, \ldots, J$) in a project
M	Number of countries m ($m = 1, \ldots, M$), $M \geq 2$
V_j	Index number of the immediate predecessors of j, $i \in V_j$
p_{jm}	Production/procurement costs of the component j in country m
w_{iljm}	Transportation costs for i from country l to country m, where j is produced
G	Estimated market value of a large-scale plant as reference to meet the expected LCR
Q	The given LCR proportion, $0 \leq Q \leq 1$

- Parameter for the project scheduling:

EFT_{jm}	The earliest finish time of activity j in country m
LFT_{jm}	The latest finish time of activity j in country m
T_{due}	Project due date with period $t = 1, \ldots, T_{due}$
d_{jm}	Duration of activity j in country m
g_{iljm}	Transport duration between j and its immediate predecessor i, if i is produced in country l and j in country m
R	Number of the renewable resources $(r = 1, \ldots, R)$
k_{jrm}	Per period usage of resource r required to perform activity j in country m
K_{rm}	Per period availability of resource r in country m

The following variables are considered:

$$x_{jm} = \begin{cases} 1 & \text{if component } j \text{ is produced/procured in country } m \\ 0 & \text{otherwise} \end{cases}$$

$$y_{iljm} = \begin{cases} 1 & \text{if component } i \text{ is produced/procured in country } l \text{ and} \\ & \text{transported to country } m\text{, where } j \text{ is produced} \\ 0 & \text{otherwise} \end{cases}$$

$$z_{jmt} = \begin{cases} 1 & \text{if component } j \text{ is produced/procured in country } m \text{ and} \\ & \text{finished at the end of period } t \\ 0 & \text{otherwise} \end{cases}$$

Objective function:

$$C_{min} = \underbrace{\sum_{j=1}^{J}\sum_{m=1}^{M} p_{jm}x_{jm}}_{\text{production/procurement costs}} + \underbrace{\sum_{j=1}^{J}\sum_{i\in V_j}\sum_{m=1}^{M}\sum_{l=1,l\neq m}^{M} w_{iljm}y_{iljm}}_{\text{transportation costs}} \tag{5.1}$$

Subject to:

$$\sum_{m=1}^{M} x_{jm} = 1 \qquad j = 1,\ldots,J \tag{5.2}$$

$$x_{il} + x_{jm} - y_{iljm} \leq 1 \qquad j = 1,\ldots,J, \quad i \in V_j, \quad m = 1,\ldots,M, \quad l = 1,\ldots,M, \quad l \neq m \tag{5.3}$$

$$x_{il} \geq y_{iljm}, \quad x_{jm} \geq y_{iljm} \qquad j = 1,\ldots,J, \quad i \in V_j, \quad m = 1,\ldots,M, \quad l = 1,\ldots,M, \quad l \neq m \tag{5.4}$$

$$\sum_{j=1}^{J}(p_{jm_0}x_{jm_0}) \geq Q \cdot G \qquad m_0 = \text{customer country} \tag{5.5}$$

$$\sum_{l=1}^{M}\sum_{t=EFT_{il}}^{LFT_{il}} tz_{ilt} \quad \leq \quad \sum_{m=1}^{M}\sum_{t=EFT_{jm}}^{LFT_{jm}} \underbrace{(t-d_{jm})z_{jmt}}_{\text{duration of activity } j} - \underbrace{\sum_{l=1}^{M}\sum_{m=1}^{M} g_{iljm}y_{iljm}}_{\text{transport duration}}$$
$$j = 2,\dots,J \quad i \in V_j \tag{5.6}$$

$$\sum_{m=1}^{M}\sum_{t=EFT_{jm}}^{LFT_{jm}} z_{jmt} = 1 \qquad j = 1,\dots,J \tag{5.7}$$

$$x_{jm} \geq z_{jmt} \qquad j = 1,\dots,J \quad m = 1,\dots,M \quad t = EFT_{jm},\dots,LFT_{jm} \tag{5.8}$$

$$\sum_{j=1}^{J} k_{jrm} \sum_{\tau=t}^{t+d_{jm}-1} z_{jm\tau} \leq K_{rm} \qquad m = 1,\dots,M \quad r \in R \quad t = 1,\dots,T_{due} \tag{5.9}$$

$$x_{jm} \in \{0,1\} \qquad j = 1,\dots,J \quad m = 1,\dots,M \tag{5.10}$$

$$y_{iljm} \in \{0,1\} \qquad j = 1,\dots,J \quad i \in V_j \quad l,m = 1,\dots,M \tag{5.11}$$

$$z_{jmt} \in \{0,1\} \qquad j = 1,\dots,J \quad m = 1,\dots,M \quad t = EFT_{jm},\dots,LFT_{jm} \tag{5.12}$$

The objective function (5.1) minimizes the total costs, which includes the production/procurement costs and the transportation costs. The constraints (5.2) to (5.5) are the ones applied to the location choice problem. (5.2) ensures that a component can be produced/procured in only one country. (5.3) and (5.4) relate the two variables x_{jm} and y_{iljm} to ensure that the transportation cost is that of the transportation from where component j was produced/procured to where it is needed. y_{iljm} can be equal to one only if both variables x_{il} and x_{jm} are equal to one. (5.5) ensures that the local content determined by the location choice should not be smaller than the given LCR.

(5.6) to (5.9) address the project scheduling problem. The constraint (5.6) combines the project scheduling and the location choice, because the durations of production/procurement and the transport durations depend on the choice of location. Furthermore, this constraint represents the precedence relations: Activity j can be started, only if all its immediate predecessors i have been finished and transported to the location where activity j is processed. (5.7) ensures that each activity is finished in exactly one country and in exactly one period, i.e. between the earliest finish time and the latest finish time. (5.8) ensures that z_{jmt} can be equal to one only if x_{jm} is equal to one. The constraint associated with (5.9) limits the period renewable resource usage to the available amount in each country. As mentioned in the last section, availability of renewable resources in each country is independent of that in another country and therefore is considered separately. To represent this specification, we use K_{rm} in (5.9) instead of K_r in standard MMPCPSP. As discussed, nonrenewable resources are not considered in this work. Finally, constraints (5.10) to (5.12) define the binary status of the decision variables.

This model realizes the integration of location and scheduling decisions to estimate the lower limit of the bid price. To evaluate this model, we generate test instances and develop a solution method in the following chapters.

6. Generation of Test Instances

In order to evaluate the mathematical model developed in the last chapter, we rely on the well-known benchmark data set generated by ProGen in the field the resource-constrained project scheduling problem. In Section 6.1 a detailed description of benchmark instances from ProGen is given. For the purpose of matching our special problem domain in the large-scale plant engineering, we modify the benchmark data set and add some new parameters in Section 6.2.

6.1. Benchmark Instances from ProGen

ProGen is a project instance generator to create benchmark instances of resource-constrained project scheduling problems. ProGen allows to generate both single- and multi-mode instances on the basis of parameters, which have been proven to have a high impact on the behavior of solution procedures. For further information on the instances sets and the project scheduling problem library PSPLIB, we refer to (Kolisch et al., 1999; Kolisch and Sprecher, 1996).

To generate benchmark instances ProGen defines three classes of input parameters (Kolisch and Sprecher, 1996):

- Fixed parameters which are constant for all benchmark sets (see Table 6.1)
- Base parameters which can be adjusted individually for each benchmark set (see Table 6.2)
- Variable parameters which are systematically varied within each benchmark set.

Table 6.1.: Fixed parameters

Parameter	Meaning
P_1^R	probability to choose a function reflecting a constant level of usage with increasing duration
P_2^R	probability to choose a function reflecting a decreasing level of usage with increasing duration
P_1^N	probability to choose a function reflecting a constant level of consumption with increasing duration
P_2^N	probability to choose a function reflecting a decreasing level of consumption with increasing duration
ε_{NET}	tolerated complexity deviation
ε_{RF}	tolerated resource factor deviation

Table 6.2.: Base parameters

Parameter	Meaning
J	total number of jobs
M_j	number of modes of job j
d_j	duration of job j
R	renewable resources
U_R	(per period) demand for a renewable resource
Q_R	number of a renewable resource requested
N	nonrenewable resource
U_N	demand for a nonrenewable resource
Q_N	number of a nonrenewable resource requested
S_1	number of start activities
S_j	number of successor activities of activity j
P_J	number of finish activities
P_j	number of finish activities

Three variable parameters are presented as follows:

- The *network complexity* (NC) stands for the average number of direct successors of an activity.

- The *resource factor* (RF) alters the average number of resources required to carry out an activity.
- The *resource strength* (RS) expresses the relationship between the resource demand of the activities and the resource availability, therefore measures the scarcity of the resources. The value of RS varies between 0 and 1. The smaller the value is, the scarcer the associated resource becomes. If RS is equal to one, there are no resource constraints, thus the optimal solution is an MPM-schedule.

Along with the generator Kolisch et al. (1992) have distributed a number of already generated instances for the single-mode and multi-mode cases.

6.1.1. Single-Mode Case

The instances for the SMRCPSP are generated with the fixed, base and variable parameter settings. Using ten instances for each combination of NC, RF, RS, the variation of these three parameters results in 480 instances of each of the first three test sets $(30, 60, 90)$ activities, and 600 instances of 120 activities. The activity durations are chosen randomly between 1 and 10. The maximum number of different renewable resources is four per activity and the resource usage for each renewable resource per period varies randomly between 1 and 10. Nonrenewable resources are not considered in the single-mode cases. The number of start (finish) activities is 3. The number of successors (predecessors) varies between 1 and 3. Time horizon T is given as upper bound on the project makespan to calculate the latest start time of the activities.

Table 6.3 presents the fixed parameter setting for SMRCPSP, and Table 6.4 the base parameter setting, while Table 6.5 illustrates the variable parameter setting.

Table 6.3.: Fixed parameter setting for SMRCPSP (Kolisch and Sprecher, 1996)

P_1^R	P_2^R	P_1^N	P_2^N	ε_{NET}	ε_{RF}
0.00	1.00	0.00	1.00	0.05	0.05

Table 6.4.: Base parameter setting for SMRCPSP (Kolisch and Sprecher, 1996)

	J	M_j	d_j	R	U_R	Q_R	N	U_N	Q_N	S_1	S_j	P_J	P_j
min	30	1	1	4	1	1	0	0	0	3	1	3	1
max	30	1	10	4	10	4	0	0	0	3	3	3	3

Table 6.5.: Variable parameter setting for SMRCPSP (Kolisch and Sprecher, 1996)

J			Parameter	levels				
30	60	90	NC	1.50	1.80	2.10		
			RS	0.20	0.50	0.70	1.00	
			RF	0.25	0.50	075	1.00	
120			NC	1.50	1.80	2.10		
			RS	0.10	0.20	0.30	0.40	0.50
			RF	0.25	0.50	075	1.00	

Computational results for SMRCPSP from Kolisch et al. (1995) show that with the increase of the *NC* the average solution time reduces. The reason is that adding more precedence relations to the network lowers the number of the feasible schedules for a given upper bound on the project makespan. This reduces the enumeration tree and makes the problem easier to solve (Kolisch et al., 1995). Since the problem is NP-complete with respect to the number of activities (Karp, 1972), the solution time grows rapidly when the number of activities increases. The increase of *RF* results in an increase of the solution time, because the average portion of resources requested per activity increases. The average solution time continuously increases with decreasing *RS*. The hardest problems are those where the minimal resource availability is provided (Kolisch et al., 1995).
In conclusion, each project characteristic shows the influence on computational time. Thereby, RS and RF are highly significant. The number of activities and NC are marginally significant, while the number of resources as well as the number of start activities are insignificant (Kolisch et al., 1995).

6.1.2. Multi-Mode Case

In the multi-mode case, the effects of the complexity, the number of constrained resources, the number of start activities and the number of activities are about the same as those in the single-mode case. Kolisch et al. (1995) focus on the effects of RF and the RS in the multi-mode case. The computational results show that RS has the strongest impact on the solution time. Moreover, multi-mode instances in general are tractable only for a very restricted number of activities. In ProGen a maximum of 30 activities is considered for the multi-mode case. For further details of this library we refer to Kolisch et al. (1992).

6.2. Defining Test Instances

The suite comes with a number of pre-generated RCPSP instances, since we are aiming at generating problem instances similar to the work done by Kolisch et al. (1995). Next to parameters we can take from ProGen directly, we need to modify two parameters in accordance to the problem at hand. A third set of parameters is added to the problem.

We take most parameters directly from the multi-mode case in ProGen and vary some of their values (see Table 6.6).

Basically, we use the single-mode instances of the set of J = $30, 60, 90$ and 120 and generate the instances with J = $150, 180, 210$ to match the problem size in the plant industry. For the instances with 30 to 120 components we set the maximal number of predecessors (MaxIn) and the maximal number of successors (MaxOut) to 3 like proposed by Kolisch et al. (1995). For instances between 120 and 210 components, we use MaxIn = MaxOut = 6. We model the situation of two production locations, i.e. customer country and contractor country, plus a possible subcontractor from the third country. Therefore we set a maximum of three countries to choose from.

The resource strength has the strongest impact on solution time, indicated in the full factorial design study from Kolisch et al. (1995). Therefore, we set the NC

Table 6.6.: Parameters taken from ProGen

Param.	Meaning	Value
J	number of components	$30, 60, 90, 120, 150, 180, 210$
M_i	number of countries	$1, 2, 3$
d_j	production/procurement time	randomly 1-10
S_1	number of start activities	3
S_j	number of successors of activity j	randomly 1-3
P_J	the total plant	1
S_j	number of predecessors of activity j	randomly 1-3
NC	network complexity	1.8
R	production resources	2
U_R	resource consumption	randomly 1-10
RF	resource factor	0.5
RS	resource availability	$0.2, 0.5, 0.7, 1.0$

and RF fixed and vary only RS: we set NC with the value of 1.8 and RF of 0.5. RS varies from 0.2, 0.5, 0.7 to 1.0.

6.2.1. Modified Instances

In order to match the special problem domain in large-scale plant engineering, some modifications to the source code of the ProGen program are made:

- Since the customer typically requests a short project duration in the Invitation to Bid, so that the given project duration cannot be as long as the time horizon described in ProGen. Therefore, we set the project duration twice the MPM-time.
- Different modes representing different countries in our case do not compete for resources. Therefore we define a resource availability for each country separately. Thus, for each country the resources form a pool to be shared

by the components produced in this country.

In the multi-mode case in ProGen, the period resource availability of each type of resource is calculated for all modes of this type of resource.

$$\sum_{j=1}^{J}\sum_{m=1}^{M_j} k_{jmr} \sum_{\tau=t}^{t+d_{jm}-1} z_{jm\tau} \leq K_r \qquad r \in R \quad t = 1,\ldots,T$$

In this work, since modes represent different countries, the period resource availability is different in each country, so that we have a K_{rm} for each mode.

$$\sum_{j=1}^{J} k_{jmr} \sum_{\tau=t}^{t+d_{jm}-1} z_{jm\tau} \leq K_{rm} \qquad m = 1,\ldots,M \quad r \in R \quad t = 1,\ldots,T$$

6.2.2. Added Instances

The following parameters are added for the special constraints in our problem:

- Production costs in different countries
- Estimated market value of a large-scale plant
- Transportation costs and - time
- Local content requirement with values of 0.3, 0.5, 0.7 and 0.9.

Our main interest refers to the size of the problem instance given by J. Furthermore we follow Kolisch et al. (1995) in assuming the resource strength to be responsible for the difficulty of a problem instance. Finally we are interested in the impact of the global LCR constraint on the solvability of a problem instance. We vary the parameter settings of RS, LCR and J (Table 6.7) and generate 10 instances for each parameter setting, i.e., $7*4*4*10 = 1120$ instances.

Table 6.7.: Variable parameter setting

J	30, 60, 90, 120, 150, 180, 210
RS	0.2, 0.5, 0.7, 1.0
LCR	0.3, 0.5, 0.7, 0.9

These instances serve as test data sets to evaluate the developed model in the next chapter.

7. The Solution Method

To solve the integrated optimization model proposed in Chapter 5 with the generated instances, we use at the first step the commercial software package ILOG CPLEX 10.0 on an Intel Core 2 Duo Processor T7200 with 2.00 GHz. Using CPLEX it is much too difficult for our model to get an optimal solution within a reasonable time for large instances and with scare resources. Therefore, we develop a solution method to solve problems with large size and complexity. The advantage of the solution method compared to CPLEX is demonstrated in the computational results.

7.1. Basic Considerations

In the integrated optimization model the location choice problem and the scheduling problem are coupled by durations. The objective of the location choice problem is to minimize the total cost, which normally leads to an increase of durations (production/procurement durations and/or transportation durations). An increase of durations may result in project delay. Decrease of durations can accelerate a project; however, the total cost may increase. In order to make a trade-off between project time and cost, constraints of LCR, the given due date and resource availability need to be considered at the same time. Different possible combinations of locations to meet all these constraints make the integrated model hard to solve.

In order to solve this problem, we make the following consideration: we divide the initial problem into two subproblems, i.e. the location choice problem and the project scheduling problem. After solving the location choice problem, we get the production location for each component, so that the initial MMRCPSP can be simplified into a SMRCPSP and therefore the problem can be solved more easily. However, we may meet a new problem: the given project due date may not be kept. The reason is the well known conflict between project time increase and cost reduction (see Figure 7.1).

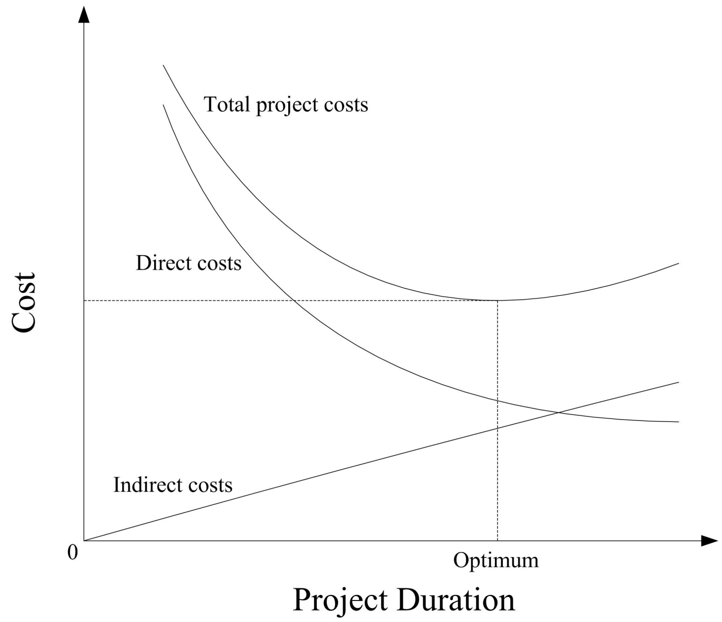


Figure 7.1.: Time and cost trade-off (Lock, 2007)

Since the purpose of location choice is to minimize costs, the project time may exceed the given due date. In order to shorten the project duration, the pace of activities should be increased. This typically results in an increase of the direct costs since more resources must be allocated to accelerate activities. In order to keep the given due date and at the same time to minimize the costs, we develop a Branch & Bound (B&B) method.

Since the given due date is a critical point when decomposing the integrated model, we relax the given due date constraint. The initial problem can then be considered as two subproblems: the location choice problem and the SMRCPSP scheduling problem. After solving the location choice problem, the location for each component is determined. The production/procurement time and transportation time are then known. Therefore, we can solve the SMRCPSP to get the project completion time. If the completion time cannot satisfy the given due date, we will subsequently modify the production location of components in order to shorten the project completion time until we find a feasible solution with costs as low as possible. The difference between the solution method of the integrated model and the model decomposition is shown in Figure 7.2:

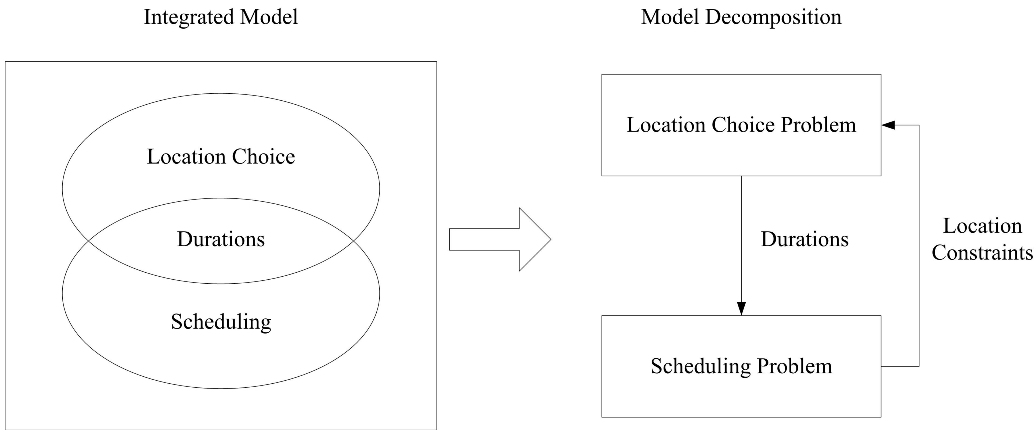


Figure 7.2.: Integrated model and model decomposition

To understand this solution method, we need to answer these questions:

1. How can the location choice problem be solved?
2. How can the SMRCPSP be solved?
3. Is the solution of both the subproblems also the solution of the integrated model?
4. If the completion time after solving the scheduling problem is later than the given due date, how can we change the production location to shorten the completion time?

The following sections of this chapter are organized to answer the above-mentioned questions:

Table 7.1.: Chapter structure

QUESTION	ANSWER
How can the location choice problem be solved?	7.2 Model Decomposition
How can the scheduling problem be solved?	7.3 Solving SMRCPSP: Priority-Rule-Based Scheduling Method - Serial Schedule Generation Schemes - Minimum Slack Priority Rule
Is the solution of both the subproblems also the solution of the integrated model?	7.4 Analysis of the Solution
How can we change the production location to shorten the completion time?	7.5 Principles of Branch and Bound 7.6 Our Branch and Bound Method 7.7 Computational Results

7.2. Model Decomposition

In order to answer the above-mentioned questions, we first decompose the initial integrated model into the location choice problem and the project scheduling problem. In the rest of this thesis, the original integrated model is called MODINT, while the model decomposition is called MODDEC.

For the location choice problem, we have the same objective function as that of the MODINT:

$$C_{min} = \underbrace{\sum_{j=1}^{J}\sum_{m=1}^{M} p_{jm}x_{jm}}_{\text{production costs}} + \underbrace{\sum_{j=1}^{J}\sum_{i\in V_j}\sum_{m=1}^{M}\sum_{l=1,l\neq m}^{M} w_{iljm}y_{iljm}}_{\text{transportation costs}} \tag{7.1}$$

Subject to:

$$\sum_{m=1}^{M} x_{jm} = 1 \qquad j = 1,\ldots,J \tag{7.2}$$

$$x_{il} + x_{jm} - y_{iljm} \leq 1 \qquad j = 1, \ldots, J, \quad i \in V_j, \quad m = 1, \ldots, M, \quad l = 1, \ldots, M, \quad l \neq m \tag{7.3}$$

$$x_{il} \geq y_{iljm}, \quad x_{jm} \geq y_{iljm} \qquad j = 1, \ldots, J, \quad i \in V_j, \quad m = 1, \ldots, M, \quad l = 1, \ldots, M, \quad l \neq m \tag{7.4}$$

$$\sum_{j=1}^{J} (p_{jm_0} x_{jm_0}) \geq Q \cdot G \qquad m_0 = \text{customer country} \tag{7.5}$$

$$x_{jm} \in \{0, 1\} \qquad j = 1, \ldots, J \quad m = 1, \ldots, M \tag{7.6}$$

$$y_{iljm} \in \{0, 1\} \qquad j = 1, \ldots, J \quad i \in V_j \quad l, m = 1, \ldots, M \tag{7.7}$$

We call CPLEX to solve the location choice problem to get the minimal costs C_{min} in the objective function (7.1). (7.2) ensures that a component can be produced/procured in only one country. (7.3) and (7.4) relate the two variables x_{jm} and y_{iljm} to ensure that the transportation cost is that of the transportation from where component j was produced/procured to where it is needed. y_{iljm} can be equal to one only if both variables x_{il} and x_{jm} are equal to one. (7.5) ensures that the local content resulting from the location choice should not be smaller than the given LCR. Constraints (7.6) and (7.7) are the decision variables for location choice.

After solving the location choice problem, the location for each component is then determined. Therefore, for each component, production/procurement time and transportation time are known. The constraints on scheduling in MODINT can then be simplified.

For the project scheduling problem, some additional parameters are introduced:

EFT_j	The earliest finish time of activity j
LFT_j	The latest finish time of activity j
T	Upper bound for the project's makespan
d_j	Duration of activity j
T_{ij}	Transport duration between j and its immediate predecessor i

Instead of z_{jmt} in MODINT, the binary decision variable z_{jt} is considered here:

$$z_{jt} = \begin{cases} 1 & \text{if activity } j \text{ is finished at the end of period } t \\ 0 & \text{otherwise} \end{cases}$$

We add an objective function aiming at the fastest possible completion time PT:

$$PT_{min} = \sum_{t=EFT_J}^{LFT_J} t z_{Jt} \tag{7.8}$$

Subject to:

$$\sum_{t=EFT_i}^{LFT_i} t z_{it} \leq \sum_{t=EFT_j}^{LFT_j} (t-d_j) z_{jt} - T_{ij} \qquad j = 2,\dots,J \quad i \in V_j \tag{7.9}$$

$$\sum_{t=EFT_j}^{LFT_j} z_{jt} = 1 \qquad j = 1,\dots,J \quad t = 1,\dots,T \tag{7.10}$$

$$\sum_{j=1}^{J} k_{jrm} \sum_{\tau=t}^{t+d_j-1} z_{j\tau} \leq K_{rm} \qquad m = 1,\dots,M \quad r \in R \quad t = 1,\dots,T \tag{7.11}$$

$$z_{jt} \in \{0,1\} \qquad j = 1,\dots,J \quad t = EFT_j,\dots,LFT_j \tag{7.12}$$

Since the location for each component is known, transportation time T_{ij} between an activity i and its immediate successor j is fixed. The constraint (5.6) in MODINT can be simplified into (7.9), which ensures that activity j can be started, only if all its immediate predecessors i have been finished and transported to the location where activity j is processed. Constraint (7.10) is also simplified due to the determination of component locations. This constraint ensures that each activity is finished in exactly one period, i.e. between the earliest finish time and the latest finish time. Constraint (7.11) limits the period renewable resource usage to the available amount in each country. Constraint (7.12) defines the binary status of the scheduling decision variable.

7.3. Solving SMRCPSP

Solution methods for the SMRCPSP can be found in Davis (1966), Herroelen (1972), Davis (1973), and Domschke and Drexl (1991), which contain the *optimal* procedures, e.g. Zero-One Programming, Implicit Enumeration with Branch & Bound, and *heuristic* algorithms, e.g. Priority-Rule-Based Scheduling, truncated Branch & Bound, Disjunctive-Arc-Based Heuristics, Local Search Techniques.

Before we describe the solution method in detail, some notations are introduced:

T_{due}	the given project due date
T_{lb}	the project earliest finish time
T_{ub}	the project completion time in consideration of resource constraints using heuristic algorithm
T_{opt}	the project optimal time resulting from calling CPLEX to solve the scheduling problem.

Steps for solving SMRCPSP are illustrated in the following.

Step 1: We use forward recursion to get the EFT of the project, which represents the lower bound of the project completion time T_{lb}:

Algorithm 3 Forward recursion

Initialization : $EST_1 = EFT_1 := 0$;
for $j := 2$ to J **do**
  $EST_j :=$ max $\{ EFT_i \mid i \in V_j \}$;
  $EFT_j := EST_j + d_j + T_{ij}$;
end for
Stop: An earliest start and finish time has been calculated for every activity;

Step 2: We use Priority-Rule-Based Scheduling to get the project completion time in consideration of resource constraints. This completion time represents the time upper bound T_{ub}.

A heuristic based on priority rules is made up of two components:

- a schedule generation scheme and

- a priority rule.

Schedule generation scheme
The two most commonly used generation schemes are *the serial scheme* and *the parallel scheme*. Both schemes build feasible project schedules by extension of a partial schedule step by step.

The *serial schedule generation scheme* was proposed by Kelley (1963). In the serial method of resource allocation, activities are sorted into a list and resources are allocated to each of these activities one at a time until resources are allocated to all activities. It is an activity oriented scheme and consists of J stages, where J is the number of activities to be scheduled. In each stage, one activity is selected and scheduled at the earliest precedence and resource feasible completion time. There are three disjoint activity sets associated with each stage (Kolisch et al., 1995):

- Complete set, in which activities are already scheduled.
- Decision set, in which activities are eligible for scheduling. All predecessors of each activity in this set are already in the complete set.
- Remaining set, in which are all remaining activities.

In each stage, an activity is chosen from the decision set in the sequence determined by a priority rule and scheduled according to the precedence and resource availability. After scheduling the activity is moved to the complete set. The decision set is updated with the immediate successors of this scheduled activity, whose predecessors have all been scheduled. The serial scheme finishes when both decision set and remaining set are empty (Kolisch et al., 1995).

The parallel schedule generation scheme was proposed by Kelley (1963) while the most used parallel algorithm was developed by Brooks (Bedworth and Bailey, 1982). In *the parallel method*, resources are allocated based on a period rather than an activity. Using this method only those activities are considered, whose predecessors have been completed. If activities compete for the same resources, the allocation of resources is based on prescribed priority rules.

Kolisch (1996) and Kolisch and Hartmann (1998) pointed out that the serial scheme is superior for large sample sizes and for instances that are only moderately resource-constrained when minimizing makespan in RCPSP. Therefore, we select the serial scheme to solve the problem at hand.

To give a detailed description of the serial scheduling scheme, some additional notations are introduced (Kolisch, 1995). At stage n, $1 \leq n \leq J$, let

C_n	be the complete set
D_n	be the decision set
R_n	be the remaining set
PS_n	be the partial schedule
πK_{rt}	be the left-over period capacity of the renewable resource r in period t
X	be the set of all activities.

Furthermore, $A_t(PS_n)$ denotes the set of activities of the partial schedule PS_n, which are in progress in period t. Then, for a given complete set C_n, the decision set D_n, the remaining set R_n, the partial schedule PS_n, and the left-over capacity πK_{rt} are defined as follows:

$$\begin{aligned}
D_n &= \{j | j \notin C_n, P_j \subseteq C_n\} \\
R_n &= X \setminus \{C_n \cup D_n\} \\
PS_n &= \{C_n\} \\
\pi K_{rt} &= K_r - \sum_{j \in A_t(PS_n)} k_{jr}
\end{aligned}$$

Finally, PST_j denotes the precedence-feasible start time and v_j denotes a priority value of activity j, $j \in D_n$. The serial scheduling scheme can then be described in the following algorithm.

Priority rules

The activities in the decision set are sorted according to the priority rules. A priority rule is made up by

- a mapping, which assigns a priority value $v(j)$ to each activity j in the decision set D_n, and
- the way the extremum of the priority values is determined, i.e. the decision whether the activity with the minimum ($extremum = min$) or maximum ($extremum = max$) priority value is selected.

Initialization: $n = 1, C_n = PS_n := \emptyset$;
while $|PS_n| < J$ **do**
UPDATE D_n, R_n, and πK_{rt}, $\quad t = 1, ...T, r \in R$;
$j^* := min_{j \in D_n}\{j | v_j = extremum_{j \in D_n} v_i\}$;
$PST_{j^*} := max\{FT_i + T_{ij} | i \in P_{j^*}\}$;
$ST_{j^*} := min\{t | PST_{j^*} \leq t \leq LST_{j^*}, \quad k_{j^*r} \leq \pi K_{r\tau}, \tau = t+1, ..., t+d_{j^*}, \quad r \in R\}$;
$FT_{j^*} := ST_{j^*} + d_{j^*}$;
$C_{n+1} := PS_{n+1} := C_n \cup \{j^*\}$;
$n := n+1$;
end while
Stop: A feasible schedule $S = (FT_1, ..., FT_J)$ has been generated;

The priority rule is presented formally as follows:

$$j^* = \min_{j \in D_n}\{j \mid v(j) = extremum_{i \in D_n} v(i)\}$$

Since j^* has the minimum $v(j)$, it has the highest priority and is selected as the first one to schedule.

Many priority rules are proposed in the scheduling literature. Publications dealing with priority rules for the SMRCPSP case can be found in Cooper (1976), Boctor (1990), and Valls et al. (1992). The following priority rules, in the order presented, have been found to be the most effective in minimizing project delay (Gray and Larson, 2008):

- Minimum slack
- Smallest duration
- Lowest activity identification number.

In order to assign resources to each activity, we use the priority rule of the minimum slack.

$$v(j) = LST_j - EST_j^{'}, \qquad \text{extremum=min}$$

$EST_j^{'}$ denotes the earliest precedence- and resource-feasible start time of activity j.

The activity with minimum slack time has a minimal priority value $v(j)$. The smaller its priority value is, the earlier the activity is selected to schedule. According to this rule, all activities in the decision set are sorted.

In order to illustrate the serial scheduling scheme and the minimum slack priority rule for our problem, we use an example project presented in Figure 7.3.

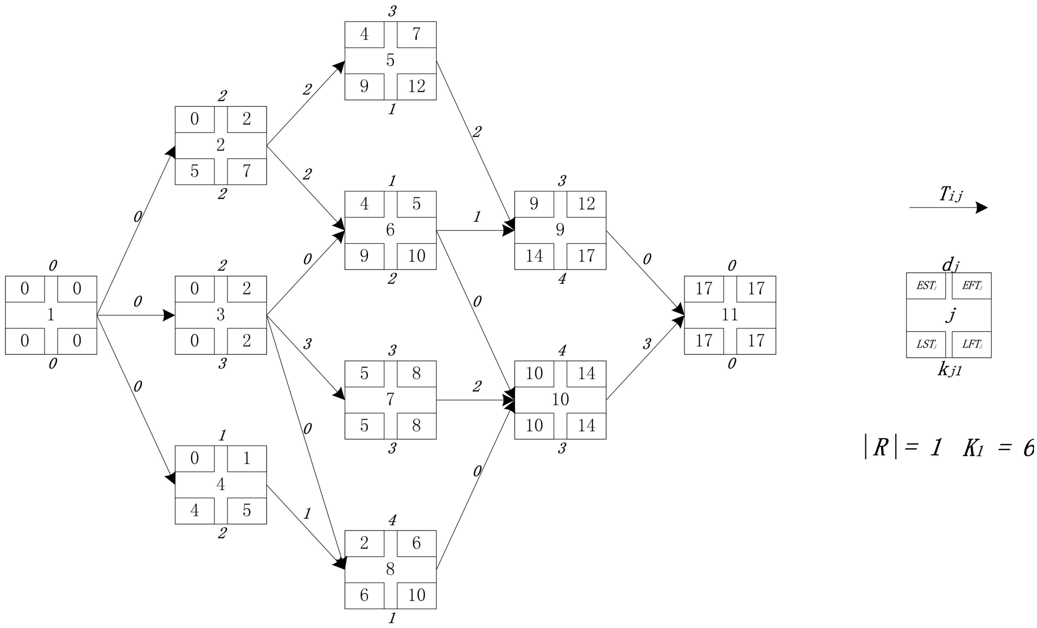


Figure 7.3.: The example project

Two critical assumptions are made before scheduling (Gray and Larson, 2008):

- No splitting activities are allowed: once an activity is placed on the schedule, it will be worked on continuously until it is finished.
- The resource level used for an activity cannot be changed.

The example project is presented as an activity-on-node network diagram. Arrows represent the precedence relationship and the transportation direction. The number on the arrow is the transportation time T_{ij}. To ease the explanation we use only one type of resource $R = 1$.

The serial scheduling scheme is described formally as follows:

Initialization: $n = 1, C_n = PS_n := \emptyset$;
while $|PS_n| < J$ **do**
UPDATE D_n, R_n, and πK_{1t}, $\quad t = 1, ...T$;
$j^* := min_{j \in D_n}\{j | v_j = min(LST_j - EST_j^{'})\}$;
$PST_{j^*} := max\{FT_i + T_{ij} | i \in P_{j^*}\}$;
$ST_{j^*} := min\{t | PST_{j^*} \leq t \leq LST_{j^*}, \quad k_{j^*1} \leq \pi K_{1\tau}, \tau = t+1, ..., t+d_{j^*}\}$;
$FT_{j^*} := ST_{j^*} + d_{j^*}$;
$C_{n+1} := PS_{n+1} := C_n \cup \{j^*\}$;
$n := n+1$;
end while
Stop: A feasible schedule $S = (FT_1, ..., FT_J)$ has been generated;

The report of the serial scheduling scheme is provided in Table 7.2.

A feasible schedule $S = (0, 3, 2, 1, 7, 5, 8, 6, 17, 14)$. The heuristic time, i.e. $T_{ub} = 17$.

In Figure 7.4 the solution of the example project is shown. The project is completed at the end of period 17 and all activities are scheduled within the resource availability.

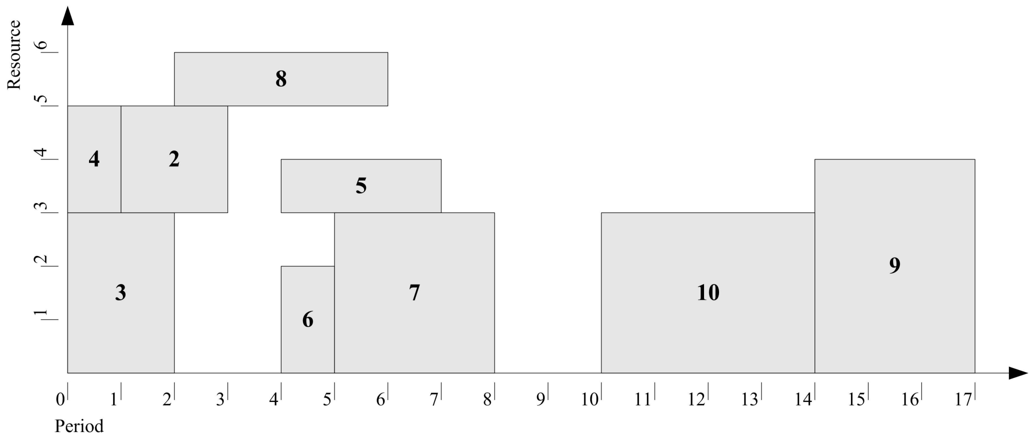


Figure 7.4.: Solution of the example project

Table 7.2.: Report of the serial scheduling scheme

n	πK_{1t}, $1 <= t <= 17$	$C_n = PS_n$	D_n	R_n	$v_{(j)}$	j^*	FT_{j^*}
1	6,6,6,6,6,6,6,6,6,6,6,6,6,6,6,6,6	$\emptyset$	1	2,...,11	0	1	0
2	6,6,6,6,6,6,6,6,6,6,6,6,6,6,6,6,6	1	2,3,4	5,6,7,8,9,10,11	5,0,4	3	2
3	3,3,6,6,6,6,6,6,6,6,6,6,6,6,6,6,6	1,3	2,4,7	5,6,8,9,10,11	5,4,0	7	8
4	3,3,6,6,6,3,3,3,6,6,6,6,6,6,6,6,6	1,3,7	2,4	5,6,8,9,10,11	5,4	4	1
5	1,3,6,6,6,3,3,3,6,6,6,6,6,6,6,6,6	1,3,4,7	2,8	5,6,9,10,11	5,4	8	6
6	1,3,5,5,5,2,3,3,6,6,6,6,6,6,6,6,6	1,3,4,7,8	2	5,6,9,10,11	5	2	3
7	1,1,3,5,5,2,3,3,6,6,6,6,6,6,6,6,6	1,2,3,4,7,8	5,6	9,10,11	5,5	5	7
8	1,1,3,5,4,1,2,3,6,6,6,6,6,6,6,6,6	1,2,3,4,5,7,8	6	9,10,11	5	6	5
9	1,1,3,5,2,1,2,3,6,6,6,6,6,6,6,6,6	1,2,3,4,5,6,7,8	9,10	11	5,0	10	14
10	1,1,3,5,2,1,2,3,6,6,3,3,3,3,6,6,6	1,2,3,4,5,6,7,8,10	9	11	5	9	17
11	1,1,3,5,2,1,2,3,6,6,3,3,3,3,2,2,2,6	1,2,3,4,5,6,7,8,9,10	11	$\emptyset$	0	11	17

7.4. Analysis of the Solution of Model Decomposition

After solving the location choice problem and the project scheduling problem, we need to check the constraint of the given due date. If the given due date can be kept, the solution of MODDEC is also the solution of MODINT. For this purpose, we compare the solution T_{lb} and T_{ub} from the scheduling problem with the given due date T_{due} resulting in the following different cases:

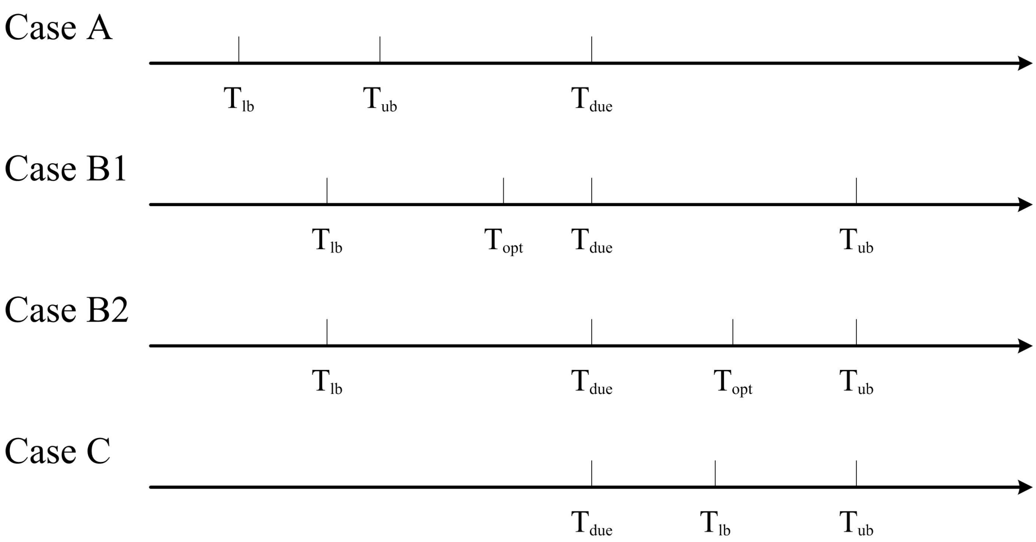


Figure 7.5.: Analysis of different cases

Case A: If $T_{due} \geq T_{ub}$, i.e. the given due date can be met, so that the solution C_{min} of MODDEC is also the solution of MODINT.
Case B: If $T_{lb} \leq T_{due} \leq T_{ub}$, we use $T_{lb} = EFT$, $T_{ub} = LFT$ and call CPLEX to solve the scheduling problem and get the T_{opt}. Here we have two situations: $T_{opt} \leq T_{due}$ (B1) or $T_{opt} > T_{due}$ (B2). In the case of B1 the given due date can be kept, so that the problem is solved. In the case of B2, since we cannot keep the due date, we need to change the location of components. In the case of C, even the earliest finish time T_{lb} is later than the T_{due}, so that we need to change the location of components.

Table 7.3 summarizes the results of the analysis:

Case	Results
Case A, Case B1	Problem is solved. C_{min} of MODINT = C_{min} of MODDEC
Case B2, Case C	The locations of components are to be changed

Table 7.3.: Results of the analysis

In order to change the component location in the case of B2 and C, we develop a Branch & Bound method.

7.5. Principles of Branch & Bound

Before we describe in detail our B&B method developed for the problem at hand, the main principles of B&B are introduced in this section. B&B is the most widely used solution technique for MIP (Martin, 1999). The B&B approach was first proposed by Land and Doig (1960) for solving integer linear programming problems (ILP). Since then, the B&B has been developed for optimization problems in the different fields of facility location (Nauss, 1978; Efroymson and Ray, 1996; Senne et al., 2005), network design (Cruz et al., 2003; Holmberg and Yuan, 2000; Günlük, 1999), traveling salesman problem (Pascheuer et al., 2000; Fischetti et al., 2003).

The algorithm is essentially a combination of two operations (Bonatesa and Hammerb, 2007; Domschke and Drexl, 2007):
(1) Branching operation: the branching operation creates new candidate problems from the current problem. The typical branching operation consists of (i) enumerating the possible values of one or more variables that can actually be realized in a feasible solution; the selection of the branching variable determines the size of the search tree, and consequently the amount of the computational effort and memory; (ii) subdivision the space of feasible solutions according to those values. Each division is called a branch and creates a restricted subproblem of the original problem. The restricted subproblem is called a descendant or a child node of the other, which is referred to as the parent node. However, branching operations do not remove any feasible solution from consideration, so

that after a branching operation the set of solutions of a problem is completely preserved in its subproblems.
(2) Bounding operation: the computation of bounds permits the elimination of a significant fraction of the subproblems. The bounding test verifies whether there are better solutions than the incumbent solution in the feasible region of the search space. An incumbent solution is the best complete feasible solution found so far. There may not be an incumbent at the beginning of the solution process. In that case, the first complete feasible solution found during the solution process becomes the first incumbent. If the solutions are worse than the incumbent and therefore will not result in any better solutions, they are eliminated from the list of candidate problems. There are three most important bounding criteria for ILP. The candidate problem is fathomed if:

1. the current solution is integer showing that the current solution is the best one in the current region

2. the current solution is worse than the incumbent solution, which indicates that any integer solution obtained from the current one will not be better than the current incumbent

3. the subproblem solution is unfeasible, that is, integer solutions do not exist in the subproblem feasible region.

In order to illustrate the B&B algorithm, we use some variations of the B&B algorithm from Land and Doig (1960), which is based on the linear programming in relaxation of (MIP). The linear programming relaxation ($\overline{MIP}$) is derived from (MIP) by deleting the integer constraints $x_j \in \mathscr{Z}$, $j \in I$.

$$(\overline{MIP}) \qquad min\{c^T x \mid Ax = b, x \geq 0\}$$

To see that $\overline{MIP}$ is a relaxation of (MIP) observe that

$$\{x \mid Ax = b, x \geq 0, x_j \in \mathscr{Z}, j \in I\} \subseteq \{x \mid Ax = b, x \geq 0\}$$

and that $c^T x$ is the objective function of both (MIP) and ($\overline{MIP}$).

A general B&B algorithm for MIP is described as follows (Martin, 1999):

Step 1: **(Initialization)** If there is a known feasible solution $\bar{x}$ to (MIP) set $z_{ub} = c^T\bar{x}$, otherwise, set $z_{ub} = \infty$. The feasible solution $\bar{x}$ giving the smallest possible value for z_{ub} is known as the incumbent and z_{ub} is an upper bound on the optimal solution value of (MIP). Solve $(\overline{MIP})$, the linear programming relaxation of (MIP). If $(\overline{MIP})$ is infeasible, then (MIP) is infeasible. If the $(\overline{MIP})$ is integer for all $j \in I$, stop with an optimal solution to (MIP). Otherwise, insert the problem (MIP) to the candidate list and go to Step 2.

Step 2: **(Problem selection)** Select a problem in the candidate list and remove it from the candidate list. Then go to Step 3. A common rule for candidate problem selection is to select the problem with the smallest linear programming relaxation value (for minimization problems).

Step 3: **(Branching)** The candidate problem under consideration has at least one fractional integer variable.

3.a Select a fractional integer variable $\bar{x}_k = n_k + f_k$ for branching purposes. Here n_k is a nonnegative integer and f_k is in the open interval $(0,1)$.

3.b Create two new mixed integer programs from the candidate problem.

- Create one new candidate problem from the candidate problem by adding the constraint $x_k \geq n_k + 1$ to the constraint set of the candidate problem.
- Create the second new candidate problem from the candidate problem by adding the constraint $x_k \leq n_k$ to the constraint set of the candidate problem.

These two new candidate problems are restrictions of the parent candidate problem since they are created by adding a constraint to the parent.

3.c Solve the linear programming relaxation of the two new candidate problems.

Step 4: (Bounding) The candidate problem is fathomed in the following situations:

(a) If its linear programming relaxation value is less than the z_{ub} and the linear programming relaxation is integer for all $j \in I$, update the incumbent value z_{ub} and make this solution the incumbent. Drop this problem from further consideration and go to Step 5.

(b) If its linear programming relaxation value is larger than the z_{ub}, eliminate this candidate problem and go to Step 5.

(c) If the linear programming relaxation is infeasible, go to Step 5.

(d) If the linear programming relaxation has at least one fractional variable $\bar{x}$, for $j \in I$ and the objective function value is strictly less than z_{ub}, add this problem to the list of candidate problems and go to Step 5.

Step 5: (Optimality Test) Delete from the candidate list any problem with an objective value of its relaxation which is not strictly less than z_{ub}. Stop, if this candidate list is empty. Otherwise, go to Step 2. If the candidate list is empty and $z_{ub} = \infty$, the problem is infeasible, otherwise, z_{ub} is the optimal solution value of (*MIP*).

Two decisions affect the effectiveness of a linear programming based on B&B algorithm greatly. They are the problem selection in Step 2 and the branching variable selection in Step 3. Land and Doig (1960) choose the node or candidate problem with the smallest linear programming relaxation value, which hopefully leads to a very good integer solution and helps to fathom dangling nodes. This is known as a breadth-first strategy. Another node selection strategy is depth-first, or last-in, first-out (LIFO). In a depth-first strategy, a single branch of the tree is developed until a feasible solution is reached or a node is fathomed. On its way back to the root the search follows the first possible alternative branch, i.e. each node is completely branched before its ancestor nodes are revisited. Most commonly, a depth-first search is organized as laser search, i.e. in the current node only one descending node is built and developed at a time (Martin, 1999).

The branching variable selection is usually based on penalty calculations. The basic idea of the penalty method is to estimate the change in the objective function value when the constraints $x_k \leq n_k$ or $x_k \geq n_k + 1$ are added. This is done by calculating the change in the objective function after one iteration of the dual simplex method (Martin, 1999). More information about penalty calculations can be found in (Beale and Small, 1965). Although branching variable selection based on the penalties is successful in some instances, it can lead to poor results for problems with large number of constraints. The basic penalty calculation is improved using the pseudo-costs method. For the detail we refer to Forrest et al. (1974).

7.6. Our Branch & Bound Method

B&B as an algorithm paradigm has to be filled out for each specific problem type. Therefore, for our problem in the large-scale plant engineering a B&B algorithm is developed.

7.6.1. The Basic Concept

Initialization
Since the given due date in Case B2 and Case C discussed in Section 7.4 cannot be kept, the problem of MODDEC indicating the initial problem P_0 is inserted into the candidate list. We set the upper bound $UB = \infty$.

Problem selection
We take an active problem P_i from the candidate list and delete it in the candidate list. At the beginning of the B&B algorithm the initial problem P_0 is the first active problem, so that $P_i = P_0$.

Build relaxation
We delete the constraint of the given due date and build a relaxation P_0' of P_0. The optimal solution value of P_0' is less than or equal to the optimal solution value of P_0. We solve the relaxation P_0'.

Branching

Since the given due date cannot be kept, we need to change locations of components to shorten the project completion time. We define a location constraint set (LCS) to store components and their fixed locations before solving a candidate problem. For the root node, i.e. the initial problem, no component is fixed to a certain country. Therefore, its LCS is empty.

Since the critical path (CP) is the longest path in the project network diagram and determines the project completion time, we can change locations of the activities on the CP to shorten the project duration. The process of changing locations of activities on the CP is a branching process. For changing locations, two key points should be considered. First, once a component's location of a node in the enumeration tree is fixed, we should ensure that the location for this component cannot be changed any more by further branching this node. Second, all locations of a component should be considered. To ease the explanation we use only two locations here. In Figure 7.6 an example of the branching process is shown. We assume that components on the CP after solving P_0' are $(2,4,7,8,\ldots,n)$, their locations are $(1,2,2,1,\ldots,1)$. After changing the location of component 2 on the CP from location 1 to location 2, we get a new subproblem P_1 with the LCS (2->2), i.e. component 2 is fixed to location 2. We change components on the CP in turn until all n components have changed their locations and we get n subproblems. Such a branching process is in line with the breadth-first strategy.

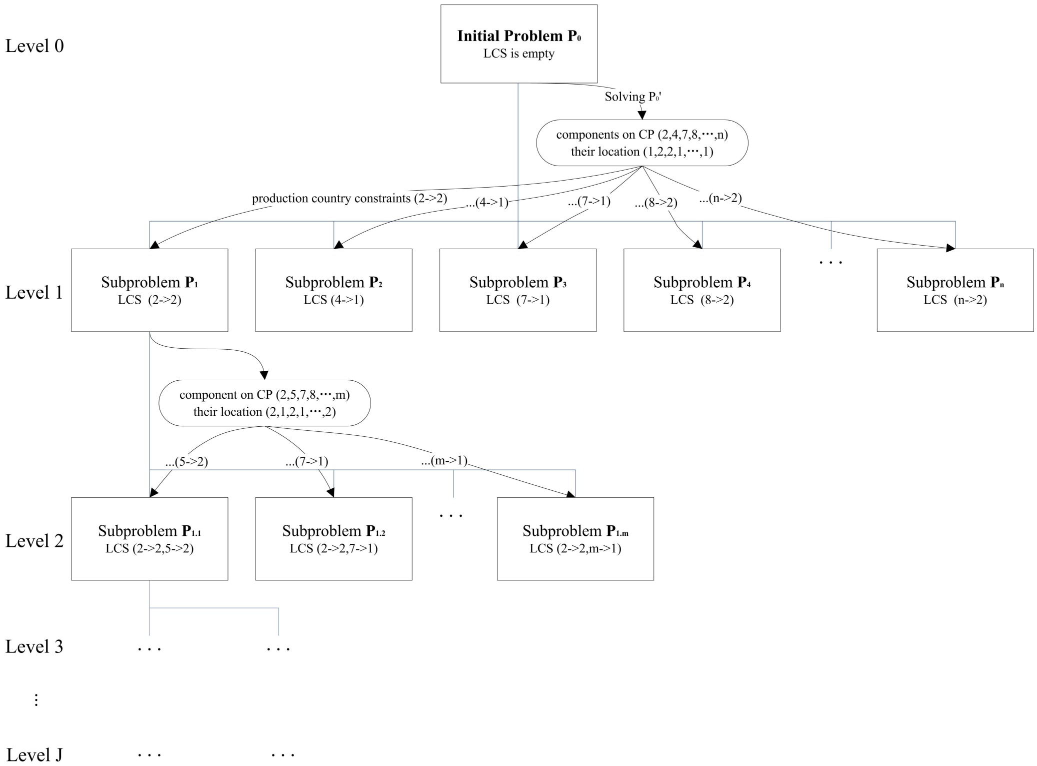


Figure 7.6.: Example of branching

Bounding

After changing the location of components on the CP, the CP, costs and LCR may change too, so that we need to solve all the new subproblems. Solve relaxation P_i' of each subproblem P_i to get the solution value SP_i', we have the following cases for each solution:

- Case A: $SP_i' \geq UB$; there is no better solution, therefore, drop this subproblem P_i from further consideration
- Case B: $SP_i' < UB$, $T_{ub} \leq T_{due}$; renew UB, P_i will not be branched anymore
- Case C: $SP_i' < UB$, $T_{lb} > T_{due}$; add the subproblem P_i into the candidate list
- Case D: $SP_i' < UB$, $T_{lb} < T_{due} < T_{ub}$; use T_{lb} as EFT and T_{ub} as LFT and call CPLEX to get T_{opt}
  - If $SP_i' < UB$, $T_{due} < T_{opt} < T_{ub}$ (Case D1), add the subproblem P_i into the candidate list

- If $SP_i' < UB$, $T_{lb} < T_{opt} < T_{due}$ (Case D2), renew UB, P_i is not branched anymore.

Use the new UB to prune the candidate list. Delete from the candidate list any problem with an objective value of its relaxation which is not strictly less than UB.

Candidate list sorting
Problems in the candidate list are sorted according to a priority rule. The problem with the highest priority is called an active problem. The following criteria form the priority rule, with which the position of a problem in the candidate is determined.

- Time, i.e. T_{lb} and T_{opt}
- Costs, i.e. SP_i'
- Number of constraints in the LCS.

These criteria are ranked according to their importance to quickly find a feasible solution, i.e. the criterion of time is more important than costs, and costs are more important than the number of constraints in the LCS. The importance of these criteria is illustrated as follows:

1. Since only problems not meeting the due date are to be inserted into the candidate list, i.e. problems in Case C and Case D1, project completion times from solving scheduling problem, i.e. T_{lb} and T_{opt}, are the most important criteria. Problems in Case D1 have higher priority than those in Case C, because the T_{due} is larger than the EFT, i.e. T_{lb} in Case D1, whereas in Case C even the T_{lb} cannot be satisfied. If both candidates have T_{opt}, i.e. both are in the Case D1. The smaller the T_{opt} is, the higher is its priority, because the possibility of its descendant to meet the T_{due} is higher. If both candidates are in the Case C, the candidate with smaller T_{lb} has the higher priority.

2. Since our purpose in this research is to minimize the project cost, the cost of each solution is a criterion to select nodes in the enumeration tree for branching. If time is identical, the lower cost determines the earlier

branching.

3. Since the branching process is also the process fixing a new production location to the LCS, the LCS determines new subproblems. The same LCS generates the same problem. If solutions of two problems have the same time and the same cost, we will compare their amounts of constraints in their LCS. Problems with less constraints are closer to the top of the search tree. Their possibility to get a feasible solution is higher, and therefore they have higher priority.

If two candidate problems are identical with all these criteria, both problems are identical; otherwise, a candidate problem will be inserted into the candidate list according to the above-mentioned priority rules.

Optimality test

If the candidate list is empty, the algorithm stops; otherwise, the active problem in the candidate list is taken out for branching. It follows the formulation and solving of relaxation as well as bounding. Such an iteration repeats until the candidate list is empty. If the candidate list is empty and $UB = \infty$, the problem is infeasible, otherwise, UB is the optimal solution value of the initial problem.

The algorithm of our B&B method is shown in the following section.

7.6.2. The Algorithm

Step1 **Initialization:** UB = ∞, initial problem P_0, let $P_i = P_0$

Step2 **Relaxation:** Build relaxation P_i' of P_i by loosing the constraint of T_{due}

Step3 **Bounding:** Solve P_i' to get SP_i' and have the following cases

Case A: $SP_i' \geq UB$; no better solution, therefore, P_i is not branched anymore, go to Step6

Case B: $SP_i' < UB$, $T_{ub} \leq T_{due}$; renew UB, P_i is not branched anymore and use the new UB to prune the candidate list, go to Step6

Case C: $SP_i' < UB$, $T_{lb} > T_{due}$; add the subproblem P_i into the candidate list

Case D: $SP_i' < UB$, $T_{lb} < T_{due} < T_{ub}$; using T_{lb} as EFT and T_{ub} as LFT and calling CPLEX to get T_{opt}

- If $SP_i' < UB$, $T_{due} < T_{opt} < T_{ub}$ (Case D1), add the subproblem P_i into the candidate list
- If $SP_i' < UB$, $T_{lb} < T_{opt} < T_{due}$ (Case D2), renew UB, P_i is not branched anymore and use the new UB to prune the candidate list, go to Step6

Step4 **Problem selection:** Select the active problem P_k from the candidate list and delete it in the candidate list

Step5 **Branching:** Branch problem P_k completely according to the CP and take each time a subproblem P_i of P_k in turn and go to Step2

Step6 **Stop:** When the candidate list = $\emptyset$.

Figure 7.7 summarizes the B&B algorithm in a descriptive flow diagram.

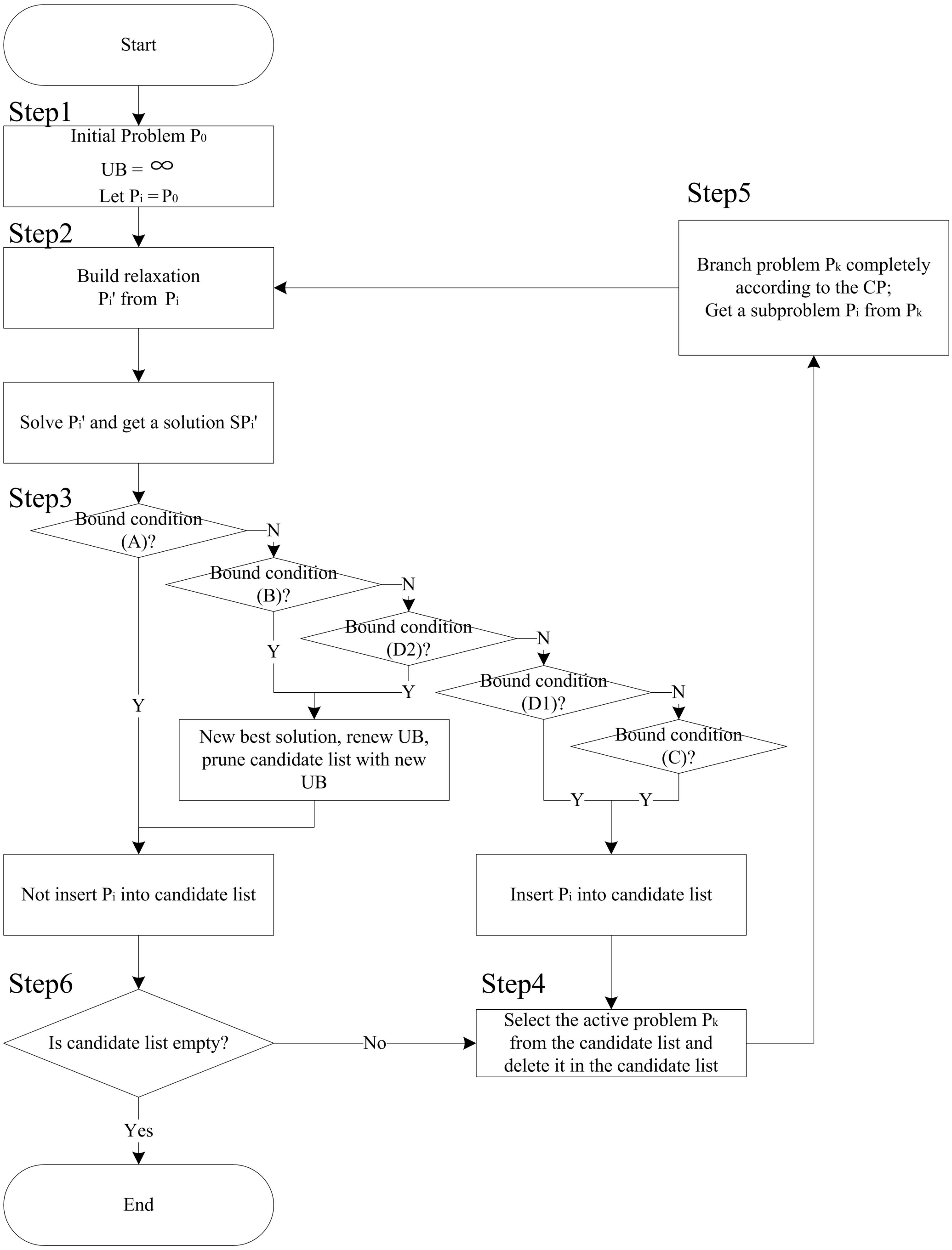


Figure 7.7.: Branch and Bound algorithm

7.7. Computational Results

In order to evaluate the B&B solution method, we use the data set generated in Chapter 6. Ten instances are generated for each parameter setting and therefore

Table 7.4.: Variable parameter setting

J	30, 60, 90, 120, 150, 180, 210
RS	0.2, 0.5, 0.7, 1.0
LCR	0.3, 0.5, 0.7, 0.9

we have totally 1120 instances. The experiments are performed using an Intel Core 2 Duo Processor T7200 with 2.00 GHz. In addition, we define a time limit of 600 CPU seconds for each instance.

As mentioned at the beginning of this chapter, we use ILOG CPLEX to solve the integrated model MODINT from Chapter 5. Therefore, in the following we illustrate not only the computational results using the B&B method, but also the comparison with results using CPLEX. Both methods use the same data sets.

The comparison of results using B&B and CPLEX are shown in Table 7.5, which summarizes all variations of LCR for a combination of RS and size. Column 1 shows the problem size. Column 2 represents the value of RS. Columns 3-6 list the results using B&B method, which include the amount of the optimal solutions and time to get them, the amount of feasible solutions and those without solutions. Columns 7-10 show the results with CPLEX. Using B&B approximately 98% instances have the optimal solutions and one instance has a feasible solution. 24 instances cannot find a solution within ten minutes, which are all problems with $RS = 0.2$. Using CPLEX 757 out of the 1120 problems, i.e. 67.5% instances can be solved to optimality. 210 problems come up with feasible solutions. 153 problems cannot find any solution, thereof 91 percent are problems with $RS = 0.2$. The average time to find an optimal solution with the B&B method is approximately 34 seconds, while it averages 129 seconds using CPLEX. For both methods the rule is, the smaller the RS is, the more difficult the problem becomes.

Table 7.5.: Computational results averaged over all LCR settings for RS = 0.2, 0.5, 0.7 and 1.0 as well as for $J = 30 - 210$ components using B&B and CPLEX.

J	RS	Optimal B&B		Feasible B&B	No solution B&B	Optimal CPLEX		Feasible CPLEX	No solution CPLEX
		#	time sec.	#	#	#	time sec.	#	#
30	1.0	40	1.10	0	0	40	2.33	0	0
30	0.7	40	1.05	0	0	40	2.09	0	0
30	0.5	40	1.06	0	0	40	2.36	0	0
30	0.2	40	1.32	0	0	40	3.49	0	0
60	1.0	40	4.49	0	0	40	27.71	0	0
60	0.7	40	4.53	0	0	40	33.14	0	0
60	0.5	40	4.67	0	0	39	43.37	0	1
60	0.2	40	29.93	0	0	33	77.88	6	1
90	1.0	40	9.70	0	0	39	94.55	1	0
90	0.7	40	9.82	0	0	38	100.95	2	0
90	0.5	40	10.77	0	0	36	100.13	4	0
90	0.2	37	50.01	0	3	13	231.62	17	10
120	1.0	40	18.14	0	0	34	185.31	6	0
120	0.7	40	18.74	0	0	26	169.59	14	0
120	0.5	40	20.02	0	0	24	176.67	10	6
120	0.2	34	80.08	0	6	2	142.03	9	29
150	1.0	40	24.21	0	0	33	161.26	7	0
150	0.7	40	24.53	0	0	33	175.74	6	1
150	0.5	40	25.27	0	0	27	200.93	12	1
150	0.2	37	93.63	0	3	2	155.88	13	25
180	1.0	40	30.99	0	0	26	201.62	14	0
180	0.7	40	31.53	0	0	22	231.93	18	0
180	0.5	40	34.76	0	0	18	234.07	19	3
180	0.2	33	83.58	0	7	0	-	2	38
210	1.0	40	64.91	0	0	31	223.70	9	0
210	0.7	40	65.41	0	0	23	175.49	17	0
210	0.5	40	66.99	0	0	18	189.54	20	2
210	0.2	34	137.21	1	5	0	-	4	36

In Figure 7.8, for $RS = 1.0$ the difference between the results using B&B and those using CPLEX is not significant. However, for $RS = 0.2$ the results using B&B are much better than those with CPLEX.

In Figure 7.9 the difference between results using B&B and those using CPLEX is very significant for each RS setting. The results of CPLEX are much worse.

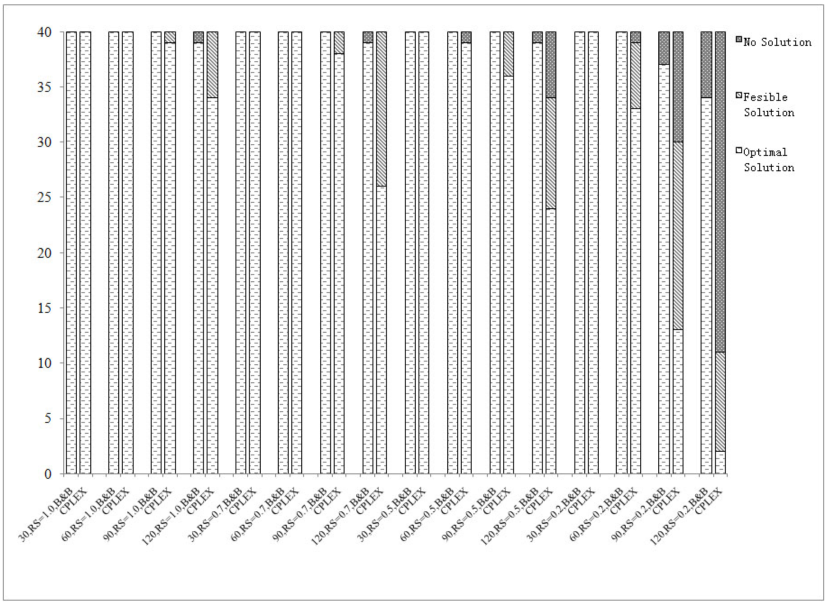


Figure 7.8.: Comparison of results of both methods: 30-120 components

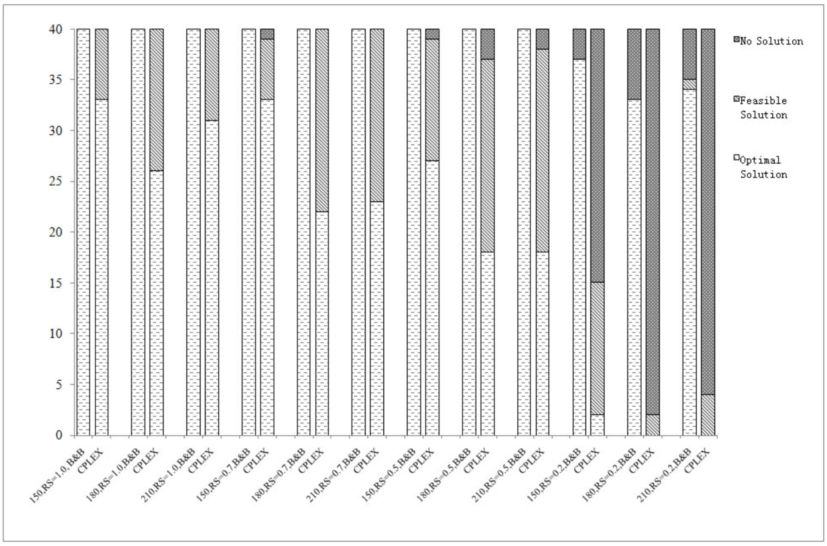


Figure 7.9.: Comparison of results of both methods: 150-210 components

In comparison with Figure 7.8, the results of using B&B in Figure 7.9 have not changed significantly, while the results of CPLEX are much more different. Using both methods, problems become harder with the increase of the problem size for both component sets from 30 to 120 and sets from 150 to 210. This trend is much more significant with CPLEX method. The computational results of B&B is better than those of CPLEX, especially for the large amount of components. Using CPLEX problems with the 30 component set can be solved to optimality in every case, while only 45 percent of the problems with the 210 component set have optimal solutions. With B&B even for the 210 component set 96% of the instances can be solved to optimality.

Table 7.6 summarizes all variations of RS for a combination of LCR and size. A small LCR is more difficult to solve than a comparably larger one.

Table 7.7 gives an overview of the gaps of the feasible solutions when using CPLEX. The first four columns list the gap results for a combination of size and RS by varying LCR. The last four columns show the gap results for a combination of size and LCR by varying RS. A gap is the difference between the feasible solution and the optimal solution divided by the optimal solution. The feasible solution is calculated using CPLEX, while the optimal solution is got from the B&B method. With the decrease of RS, gaps become larger (see Column 4). The smaller the LCR is, the larger the gap gets (see Column 8).

For the one feasible solution of the B&B method, we calculate its gap to the LB and get the value of 0.05%.

Table 7.6.: Computational results averaged over all RS settings for LCR = 0.3, 0.5, 0.7 and 0.9 as well as for $J = 30 - 210$ components using B&B and CPLEX.

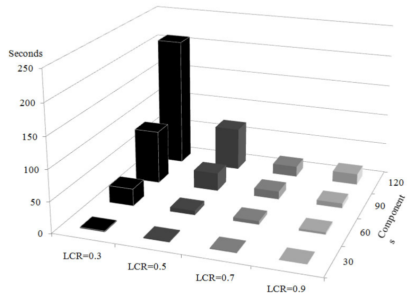
J	LCR	Optimal B&B		Feasible B&B	No solution B&B	Optimal CPLEX		Feasible CPLEX	No solution CPLEX
		#	time sec.	#	#	#	time sec.	#	#
30	0.9	40	0.45	0	0	40	0.90	0	0
30	0.7	40	1.08	0	0	40	2.17	0	0
30	0.5	40	1.48	0	0	40	3.62	0	0
30	0.3	40	1.51	0	0	40	3.58	0	0
60	0.9	40	3.36	0	0	40	15.26	0	0
60	0.7	40	5.48	0	0	40	35	0	0
60	0.5	40	6.81	0	0	39	82.42	1	0
60	0.3	40	27.97	0	0	33	44.56	5	2
90	0.9	40	7.67	0	0	38	55.42	2	0
90	0.7	40	12.91	0	0	33	143.31	4	3
90	0.5	40	29.42	0	0	27	139.40	9	4
90	0.3	37	86.83	0	3	28	126.44	9	3
120	0.9	40	17.67	0	0	31	90.03	1	8
120	0.7	40	17.14	0	0	27	232.70	6	7
120	0.5	38	69.61	0	2	18	174.48	14	8
120	0.3	36	209.92	0	4	10	302	18	12
150	0.9	40	14.40	0	0	31	48.64	7	2
150	0.7	40	21.49	0	0	28	186.47	6	6
150	0.5	38	115.30	0	2	14	341.84	17	9
150	0.3	39	78.88	0	1	22	242.87	8	10
180	0.9	40	29.98	0	0	30	137.05	0	10
180	0.7	40	59.46	0	0	11	336.47	18	11
180	0.5	40	49.33	0	0	10	339.05	21	9
180	0.3	33	222.97	0	7	15	223,65	14	11
210	0.9	40	34.67	0	0	29	139,63	3	8
210	0.7	40	121.15	0	0	14	318,31	16	10
210	0.5	38	153.73	0	2	10	183,17	21	9
210	0.3	36	153.32	1	3	19	212.91	10	11

Table 7.7.: Gaps to the optimal solutions using CPLEX for a combination of RS and size by varying LCR and for a combination of LCR and size by varying RS.

J	RS	Feasible #	Gap to opt.	J	LCR	Feasible #	Gap to opt.
60	0.2	6	0.57%	60	0.3	5	0.57%
90	1.0	1	0.01%	60	0.5	1	0.28%
90	0.7	2	0.23%	90	0.3	9	0.80%
90	0.5	4	0.11%	90	0.5	9	0.18%
90	0.2	17	0.49%	90	0.7	4	0.10%
120	1.0	6	0.08%	90	0.9	2	0.06%
120	0.7	14	0.14%	120	0.3	18	0.23%
120	0.5	10	0.29%	120	0.5	14	0.20%
120	0.2	9	0.32%	120	0.7	6	0.21%
150	1.0	7	0.20%	120	0.9	1	0.02%
150	0.7	6	0.19%	150	0.3	8	0.24%
150	0.5	12	0.14%	150	0.5	17	0.18%
150	0.2	13	0.14%	150	0.7	6	0.09%
180	1.0	14	0.12%	150	0.9	7	0.07%
180	0.7	18	0.18%	180	0.3	14	0.19%
180	0.5	19	0.20%	180	0.5	21	0.21%
180	0.2	2	0.29%	180	0.7	18	0.12%
210	1.0	9	0.09%	210	0.3	10	0.16%
210	0.7	17	0.13%	210	0.5	21	0.13%
210	0.5	20	0.12%	210	0.7	16	0.06%
210	0.2	4	0.16%	210	0.9	3	0.04%

In Figure 7.10 the impact of varying the amount of components, RS and LCR on the runtime is documented. As the resource becomes scarce, problems turn to be harder to solve. This is consistent with the observation of Kolisch et al. (1995). With the increase of LCR, problems become easier. The results demonstrate that the model proposed is well suited for a coarse grained consideration of a project's WBS of up to a few hundred components.

In conclusion, the computational results demonstrate the advantage of the developed B&B method compared to the CPLEX approach. Problems become harder



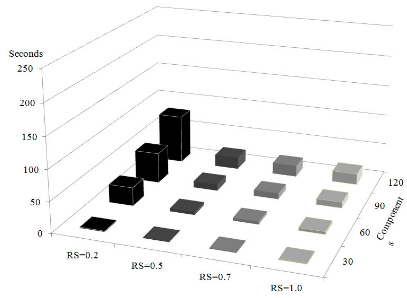


Figure 7.10.: Effects of LCR and RS on different J configurations

with the increasing scarcity of resource. A higher LCR reduces the computational time. The larger the problem size becomes, the longer it takes to get a solution. As shown in the computational results, the hardest problems are those with the RS value of 0.2. In practice, if available resources are very scarce, the plant manufacturer faces a higher risk of a project delay. Therefore, he may make a no-bid decision, or he suggests a longer project duration than that demanded by the customer. In the following chapter, we present an application case to show the support of our model to make such a decision.

8. Decision Support for Bidding and Negotiation

In order to demonstrate the advantage of our model for decision support in bidding and negotiation, we present figures of an up-to-date malting plant project, which Bühler started in 2007 in China. This malting system consists of 207 components and will process 100,000 tons of malt per year. The following data enter the optimization:

- Quantity and type of the 207 plant components are described in the bill of quantity.
- The production costs of components are estimated from experience of former projects.
- Each component of the bill of quantity forms an activity in the project network.
- The prospective duration of an activity is estimated from experience.
- Precedence relations of activities are known from the technical specification.
- Transportation costs for components are known from experience and freight tariffs.
- The project due date is prescribed by the client.
- An LCR of 50 – 80 percent is requested.
- One component carrying core technology of Bühler is to be exclusively

produced in Germany.

Production locations for the remaining components are subject to optimization. Using the developed model, the problem is solved in 0.26 seconds on a standard PC. Possible scenarios in the bidding and the negotiation phase are depicted in Table 8.1.

Table 8.1.: Scenario analysis

No.	LCR (%)	know-how protect (number)	deviation from duration D (week)	components in China (%)	deviation from minimal cost C (%)
1	50	0	0	85	0
2	50	1	+2	83	+0.6
3	50	1	0	79	+2.8
4	80	1	0	91	+3.8
5	80	1	+4	91	+3.1

In order to keep sensitive data with Bühler, we use D to represent the project duration demanded by the client. Under this constraint, C represents the minimal costs determined by the problem instances. Using the above-mentioned parameter setting, 85 percent of the total amount of components are chosen for production in China (No. 1). Since an important component contains core technology of Bühler, this component should be produced in Germany. Fixing this location decision while relaxing the project duration constraint, costs increase by 0.6 percent and the project duration lengthens by two weeks (No. 2). While the reasonable increase of costs seems acceptable, the extension of the project duration will hardly be tolerated by the client. Fixing the project duration at D again, the total costs now increase by 2.8 percent (No. 3), i.e. $C*(1+2.8\%)$. This figure is accepted by Bühler as a lower limit of the bid price.

The client prefers Bühler as contractor due to the reasonable price and the assured high quality. However, we assume that the client starts bargaining for an LCR of 80 percent in the negotiation phase. Now the costs for Bühler increase by 3.8 percent, which seems hardly acceptable (No. 4). In order to acquire the contract, Bühler suggests a lengthening of D by four weeks resulting in a decrease of costs from 3.8 to 3.1 (No. 5). In comparison to the lower limit of the bid price shown in No. 3, an increase of $3.1 - 2.8 = 0.3$ percent is acceptable by Bühler in order to acquire this project. In case that the client insists on the originally requested due date D, Bühler will reject the project in order to protect its know-how.

In conclusion, our model supports the process of obtaining the minimal costs for a specific project parameter setting in the bidding procedure. In the negotiation phase, our model can support a contractor to make the right decisions under changing trading conditions. By means of the scenario analysis the contractor can keep a reasonable negotiation position and can avoid losses due to the lack of information.

Our model and its outcome have been carefully validated by project managers of Bühler. Norbert Heide, senior project engineer at Bühler AG, Braunschweig, writes: "The developed system enables the minimization of project costs under a given project due date within a short computational time. Significant positive results were achieved in the saving of calculation time and manpower for the bid generation as well as in decision-making during the contract negotiation.

"On the basis of our experience gained in practice in recent years we confirm that the local content requirement has been increasing more and more in the field of international plant engineering and construction. This is true especially in the fast growing Asian countries like China, India and Vietnam.

"We consider the problems such as choice of the production location, transfer times, short project fulfillments periods as well as the potential danger of know-how flowing off already in the quotation phase, since these problems cause high demands on the elaboration and assessment of the plant quotation with regard to its individual components.

"As common in plant engineering, we use configuration software for a plant's technical specification during bid generation. In view of the large number of plant components, some of which being very complex, it is mandatory to have a decision support software. The model developed by Yang and Mattfeld enhances our configuration software by means of decision support for bid generation and negotiation with customers. Therefore, the solutions presented here are of particular importance to Bühler."

Our model is not only useful for malting projects, but also appreciated by other industries. Klaus Gottwald, analyst of the German VDMA's Large Industrial Plant Manufacturer's Group, writes: "Acting in an extreme competitive environment, the German large plant manufacturing sector is confronted with continuing high pricing pressure. The necessity to complete major projects on budget and on time requires a complex price finding system. Increasing local content requirements and decreasing project duration lead to decision problems in the fields of location choice and project scheduling. Cost efficiency is more important than ever.

"In response to these current challenges Jiayi Yang and Dirk C. Mattfeld focused in their detailed study on the decision support of the lower limit for bid prices by minimized project costs. The main goal of the study is to develop a coherent strategy of bid price estimating. Analyzing the interrelation between location choice and project scheduling, they created a mathematical tool which enables plant suppliers to improve their price finding system. The mathematical optimization model is combining international facility location problems with resource-constraint project scheduling in consideration of local content requirements.

"Performing the highest potential at every level, German large plant manufacturers need a suitable support instrument which enables an efficient choice of location. The tool developed by Yang and Mattfeld can make a major contribution to business success, thus significantly reducing operating costs. The implementation of the instrument at the renowned engineering company Bühler GmbH shows this clearly. The findings of the two scientists are, however, not only useful for companies in the field of food plant engineering but will also provide great support for other important sectors of the large industrial plant engineering industry as, to mention only a few, the manufacturers of power stations, steel plants and construction material facilities."

9. Summary and Outlook

In this chapter, we reflect on the thesis as a whole. The contribution of this research is then clarified. Furthermore, possibilities for future research are discussed.

9.1. Overview of Current Work

The motivation of this dissertation is the increase in demand for international large-scale plant orders in the last years. However, the international orders have to meet challenges of the current worldwide economic downturn, the high pricing pressure, the increasing local content requirement, and the short project duration. Against this background, the purpose of this research is to support the bid price estimate by minimizing costs in consideration of the above-mentioned challenges. In the following the most important results and conclusions of this dissertation are presented.

After a brief motivational introduction in Chapter 1, specifications of the large-scale plant industry in Germany are illustrated in Chapter 2. Beginning with some basic definitions of the term industrial plant, the scope and features of a large plant are discussed in Section 2.1. Section 2.2 gives an overview of the German large-scale plant industry, its importance to the German economy and the competence of the German plant manufacturers. It follows the illustration of segments of this industry, especially the process plants, and the market situation of each segment. The major sales success in the last years results not only from the increasing demand, but also from the competence of German manufacturers in plant engineering. Therefore, in Section 2.3 a detailed description of plant engineering is given. The design and construction of a large plant require the interaction of technical, commercial and construction skills and methods. To manage such a complexity, project management approaches should catch more attention. However, the process plant industry has not got enough consideration by project management researchers (Fransoo and Donk, 2003), (Zobel and Wearne, 2000). Facing the economic slowdown, German plant constructors should rely on their competence in the project management to reduce project costs and time to survive the sales slump and the intensive competition.

Since large plant manufacturing is performed in form of a project, project management as an efficient instrument to reach plant project objectives is introduced in Chapter 3. After providing the definition of a project, its characteristics and possible objectives, we put our focus on the project life cycle special for the plant industry in Section 3.2. The plant project life cycle is divided into two phases: project planning and project execution. Before a large plant project can be executed, an order contract between client and plant manufacturer must be signed, which is realized typically through bidding and negotiation processes in the planning phase. After the bidding process, bidders with lower bid price meeting a client's requirements are selected by the client for a further negotiation. Normally, the bidder with the lowest bid price wins the contract. Due to the importance of the bidding process for an award of a plant contract, its components, i.e. technical design, bid price estimates and project scheduling, are illustrated in detail. In the design of project deliverables, a product breakdown structure is conducted to determine what is to be produced in the project, while a work breakdown structure focuses on how the work products and project solution will be built. Both provide the basis for the bid price estimating and project scheduling. The objective of an estimate is to determine the optimal bid price to have the best chance of winning a contract and making a profit. In order to get leeway in pricing, the lower limit of a bid price must be known, which is based on cost estimating. In Section 3.4 cost elements serving as basis for calculation and different estimating methods applied to various accuracy classes of estimates are introduced. Due to the high cost for bid generation and the low bid success rate, the accuracy and effort of bid estimates should be adapted to its chance of success. We rely on AACE classification to identify the accuracy classes and the estimating methods of each class. Section 3.5 focuses on the project scheduling. It begins with the explanation of scheduling elements, e.g. activities, duration, precedence relations and resources, and continues with the description of different ways to represent a project schedule, whereby the critical path method is chosen to conduct the project network diagram and calculate the project completion time. Typical project scheduling problems, i.e. single-mode resourced-constrained project scheduling problem and multi-mode project scheduling problem, are depicted at the end of this section to support the understanding of scheduling issues in large plant projects.

In Chapter 4, we first describe the current situation in international plant market, which has been affected significantly by the worldwide economy slowdown since the second half-year of 2008. The resultant challenges are addressed in Section 4.2, which are characterized by

- falling demands and uncertainty due to the worldwide economic downturn
- intensive competition not only from industry countries but also from developing countries leading to high pricing pressure
- shorter project duration demanded by clients to realize quick amortization of their investment and reduce financial risks
- Euro's appreciation against the dollar resulting in negative effects on German plant constructor's export.

In addition, latent protectionism in form of local content requirement results in a reduced domestic portion of the total project value for plant manufacturers and a possible know-how drain. Furthermore, more competitors result in more submitted bids, so that the success rate of bids drops. Uncertainty and risks due to the lack of precise information in foreign markets have increased. The scope of requirements in bid document has been expanded leading to more efforts.

Under these hard challenges, costs must be optimized in order to keep a reasonable low bid price. The accuracy of cost and time estimates must be improved, because project cost and time overruns can result in a large financial loss. Cost and time for bid generation must be reduced, since the bidder must bear their own costs of bidding. Therefore, German large plant manufacturers take their advantage of the global presence and make sourcing and/or production in low-cost countries to provide low bid prices. However, global sourcing may lead to high transportation costs and longer production or procurement time due to inadequate worker skills, infrastructural deficiencies, supplier unavailability. The quality scheme in such countries could also be a problem. Additionally, global sourcing carries risks of variability and uncertainty in currency exchange rates. Furthermore, a high LCR restricts the scale of global sourcing in the other countries. In conclusion, plant constructors must make an adequate location decision to satisfy local content rules and garner some of the advantages of global sourcing. At the same time, the given project due date should not be put at risk.

The response to challenges in the bid generation is illustrated in a case study of the large-scale plant constructor Bühler in Section 4.3. Bühler uses a configuration software to support the bid calculation. Due to the worldwide production sites of Bühler, components of a plant can be produced in different countries with different costs and time. In order to submit a low bid price, location decisions should be involved in the bid generation. Since the scheduling is dependent on the location choice, the choice of location has to be prescribed. However, the configuration software cannot support such a decision. Therefore, the objective of this research is to develop a tool supporting cost optimization and accurate estimation of the lower limit of the bid price. To achieve this objective, we analyze the interaction of location choice and project scheduling in Section 4.4. The local content depends directly on the choice of location. In turn, the choice of location is restricted by the given local content requirement. The time needed to produce a component in turn depends significantly on the location. In this way, the location can affect the duration of the entire project. Especially limited capacities in a location may delay a project. The location and scheduling decisions interact with each other and should be involved in the bidding process. However, such an integration is still missing.

In Chapter 5 we focus on finding a solution to integrate both location and scheduling decisions. For this purpose, we review the relevant literature in the field of the global network design problem and the resource-constrained project scheduling problem. With respect to the general aspects of location decisions discussed in the relevant literature, we identify the basic features of our problem at hand. Due to the different locations possible for production of components, the problem of a large-scale plant project is similar to the multi-mode resource-constrained project scheduling problem representing different ways to perform a certain activity. However, there are still some differences between the general MMRCPSP and our scheduling problem. In this work, each mode, i.e. each country, has its own resource availability. Furthermore, nonrenewable resources are not considered. On the basis of the literature review and in consideration of the interaction of the location choice and project scheduling, we propose a mathematical model to combine the model of the international facility location problem and the model of MMRCPSP in Section 5.2. The objective function minimizes the total costs including the production or procurement costs and the transportation costs. Constraints, i.e. LCR, the given project due date, precedence relations of activities, and the resource availability are considered.

In order to evaluate the optimization model with maximal solvable project size and under scarce resources, we are engaged in Chapter 6 the ProGen benchmark instance sets developed in the field of resource-constrained project scheduling. Different parameter settings for the single-mode and multi-mode cases are introduced. We take most parameters directly from the multi-mode case in ProGen, but vary some of their value in order to match our problem at hand, e.g. we extend the number of activities to 210; we do not consider the nonrenewable resource, so that its value is equal to zero. Furthermore, we make some modifications and add some new parameters to match the special problem domain in large-scale plant engineering. In order to meet the short project duration demanded by plant clients, we shorten the horizon (upper bound on the projects makespan) described in ProGen to doubled MPM-time. Since different modes representing different countries in our case do not compete for resources, separate resource availability is defined for each country. In addition, production costs in different countries, transportation costs and time, estimated market value of a large-scale plant, different local content requirements are used as additional parameters for the special constraints of the optimization problem.

To solve the mathematical model with the generated instances, at the first step we apply the commercial software package ILOG CPLEX 10. Computational results have shown that by using CPLEX almost all problems of small size up to 60 activities can be solved to optimality within a short time; but it is much more difficult to use CPLEX to get an optimal solution for problems with large size and with scarce resources within reasonable time. Therefore, we propose a B&B solution method for problems with large size and complexity in Chapter 7. It begins with the basic consideration: if we divide the initial problem into two subproblems, i.e. the location choice problem and the project scheduling problem, we get the production location for each component after solving the location choice problem, so that the initial MMRCPSP can be simplified into a SMRCPSP. The complexity of the problem is reduced and therefore easier to solve. Under this consideration Section 7.2 follows the model decomposition, i.e. the model integrating the location choice problem and MMRCPSP developed in Chapter 5 is decomposed into two sub models - the location choice model and the model of SMRCPSP. We call CPLEX to solve the location choice problem. For solving SMRCPSP, we use the Priority-Rule-Based Scheduling method, which consists of a serial schedule generation scheme and a minimum slack priority rule. After solving both problems, we consider different cases related to the given project due date constraint. In case the given due date cannot be kept, a B&B method is developed. Before a detailed illustration of our B&B method is given, principles of B&B are introduced in Section 7.5. The branching and bounding operations as well as the general B&B algorithm are illustrated in detail. Since B&B as an algorithm paradigm has to be filled out for each specific problem type, we develop a B&B specified for our problem in large-scale plant engineering in Section 7.6. We loose the constraint of the given due date to build a relaxation of the initial problem. Such a relaxation is represented by the decomposed model, i.e. the location choice problem and the SMRCPSP. We take each time an active problem from the candidate list and branch it by changing the location of its components on the critical path to shorten the project duration. This branching process is different from the general B&B method, where variables are branched in the branching operation. Once a component is fixed to a certain location, a new subproblem is created. Using the breadth-first strategy we change the components on the critical path in turn until a problem is completely branched. Relaxations of the new subproblems are solved and the solution values are compared to the current upper bound. If the solution is worse than the upper bound, the subproblem is pruned. If the solution is better and the given due date can be kept, the upper bound is renewed. In case where the solution value is better, but the given due date cannot be kept, the subproblem is inserted into the candidate list. The candidate list is sorted according to the criteria, i.e. the time including the earliest finish time and the optimal time after calling CPLEX, the costs after solving the relaxation, and the number of components, whose locations are fixed. The B&B algorithm is terminated when the candidate list is empty. The whole algorithm is documented in Section 7.6.2. Computational results using the data set generated in Chapter 6 demonstrate the advantage of the B&B method. Approximately 98% of the instances can be solved to optimality using the B&B method within a time limit of ten minutes, whereas only 67.5% instances using CPLEX have the optimal solution. The average time to find the optimal solution with B&B is much shorter, only 26% of the calculation time using CPLEX. Scarce resources make the problem harder to solve. The computational time increases with the increase of the problem size. The problem becomes easier when the value of LCR gets smaller. In a word, the proposed B&B is proven to be a cost and time efficient method to support location and scheduling decisions in the bidding process.

Chapter 8 presents an application case demonstrating the decision support of the developed model in the bidding and negotiation phase. From the malting plant manufacturer Bühler we get the plant data of an ongoing malting plant project, which consists of 207 components. Possible locations are production sites in Germany and China. In order to protect know-how, a key component can only be produced in Germany. Under support of the model and the solution method developed in this work, this problem is solved to obtain the minimal costs for a specific project parameter setting within one second. The case study not only serves as a proof-of-concept for the model, but also intends to convey the value of applying operations research techniques for the decision support in large-scale plant engineering. The application case demonstrates that significant improvement regarding project cost and time in the bidding process can be achieved. Furthermore, the model supports a scenario analysis in the negotiation phase, which helps a plant manufacturer to make right decisions under changing trading conditions, so that he can keep a reasonable negotiation position and avoid losses due to the lack of information.

Finally, Chapter 9 contains a brief overview and discussion of this dissertation, as well as an outline of future research that will address important questions of the large-scale plant engineering.

In conclusion, the following aspects highlight the individual contributions:

- Presentation of the interrelation between LCR, location choice, and project scheduling
- Development of a mathematical model for decision support
- Design of tractable solution algorithms for the problem of large size and complexity
- Validation of the model with benchmark instances generated by ProGen in the field of RCPSP
- Demonstration of the decision support of the model in bidding and negotiation processes of the plant engineering.

Overall, the objective of the dissertation is achieved. In the process of developing this research, a variety of interesting research questions is generated and briefly outlined in the following section.

9.2. Future Research

In what follows, possible directions for future research are briefly described.

In the proposed B&B method, we call CPLEX to get the minimal costs for each problem and the optimal project time when the given due date is between the earliest finish time and the time upper bound calculated with the Priority-Rule-Based Scheduling method. For calling CPLEX each time all data are read once consuming a lot of time. In the further research, algorithms could be developed to replace calling CPLEX to improve the computational results.

In this work we focus on the estimation of the lower limit of a bid price, because it is important for a company to review costs associated with the bid price of a project in order to analyze the effect of costs on the projected bid price.

On this basis and in consideration of other influence factors, further research supporting bid price formulation is desirable. A marketing-driven supplier should set its pricing based on market value, market strategy, future opportunities and repeat business, and the company's need. In addition, a bid price must include design considerations, which cover unit efficiency, inputs and outputs, and the advantages/disadvantages relative to competitor designs. Furthermore, a bid price must consider the customer's financial position (Bases, 2004).

Since the commercial configuration softwares, used typically in the large-scale plant projects, do not support decision-making in the bidding and negotiation processes, a decision support system supporting integrated location choice and project scheduling could be an innovative solution for the large plant industry, which can catch attentions for further research.

Bibliography

ANSI Standard. Industrial engineering terminology: Cost engineering, 1989.

B. Arntzen, G. Brown, T. Harrison, and L. Trafton. Global supply chain management at digital equipment corporation. *Interfaces*, 25:69–93, 1995.

K. Backhaus. *Industriegütermarketing (8. Auflage)*. Verlag Vahlen, 2007.

K. Backhaus and R. Weiber. Das industrielle Anlagengeschäft - ein Dienstleistungsgeschäft? In H. Simon, editor, *Industrielle Dienstleistungen*, pages 67–89. 1993.

K. Baker. *Introduction to sequencing and scheduling*. Willey, 1974.

H. Balck. *Networking und Projektorientierung*. Springer, 1996.

A. Baldwin, R. McCaffer, and S. Oteifa. *International bid preparation*. International Labour Org, 1999.

G. Bases. Understanding the bidding process - from both sides. *Foundry management & technology*, 132(2):19–22, 2004.

E. Beale and R. Small. Mixed integer programming by a branch and bound technique. pages 450–451, 1965.

D. Bedworth and J. Bailey. *Integrated Production Systems - Management, Analysis, Design*. Wiley, New York, 1982.

A. Belout and C. Gauvreau. Factors influencing project success: the impact of human resource management. *International Journal of Project Management*, 22:1–11, 2004.

J. Blazewicz, J. Lenstra, and A. R. Kan. Scheduling subject to resource constraints: classification and complexity. *Discrete Applied Mathematics*, 5:11–24, 1983.

F. Boctor. Some efficient multi-heuristic procedures for resource -constrained project scheduling. *European Journal of Operational Research*, 49:3–13, 1990.

T. Bonatesa and P. Hammerb. A branch-and-bound algorithm for a family of pseudo-boolean optimization problems, 2007.

G. Bounds. The last word on project management. *IIE solutions*, 30:41–43, 1998.

R. L. Breitman and J. M. Lucas. Planets: A modeling system for business planning. *Interfaces*, 17:94–106, 1987.

C. Chilton. Six-tenths factor applies to complete plant cost. *Chemical Engineering*, 57:112–114, 1950.

P. Christensen and L. Dysert. Cost estimate classification system - as applied in engineering. procurement, and construction for the process industries, 2005.

D. Cleland and L. Ireland. *Project Management: Strategic Design and Implementation, 5 Edition*. McGraw-Hill Professional, 2006.

M. Cohen and H. Lee. Resource deployment analysis of global manufacturing and distribution networks. *European Journal of Manufacturing and Operations Management*, 2, 2:81–104, 1989.

M. Cohen, M. Fisher, and R. Jaikumar. International manufacturing and distribution networks: a normative model framework. In K. Ferdows, editor, *Managing International Manufacturing*, pages 67–93. Elsevier Science Publishers, 1989.

T. Cooke-Davies. Establishing the link between project management practices and project success. 2002.

D. Cooper. Heuristics for scheduling resource-constrained projects : An experimental investigation. *Management Science*, 22(11):1186–1194, 1976.

F. Cruz, G. Mateus, and J. Smith. A branch-and-bound algorithm to solve a multi-level network optimization problem. *Journal of Mathematical Modelling and Algorithms*, 2(1):37–56, 2003.

N. Damak, B. Jarboui, P. Siarry, and T. Loukil. Differential evolution for solving multi-mode resource-constrained project scheduling problems. *Computers & Operations Research*, 36:2590–2600, 2009.

E. Davis. Resource allocation in project network models - a survey. *The Journal of Industrial Engineering*, 17:177–188, 1966.

E. Davis. Project scheduling under resource constraints - historical review and categorisation of procedures. *AIIE Transactions*, 5:297–313, 1973.

W. Domschke and A. Drexl. *Einführung in Operations Research*. Springer, 2007.

W. Domschke and A. Drexl. Kapazitätsplanung in Netzwerken - Ein Überblick über neuere Modelle und Verfahren. *OR Spektrum*, 13:63–76, 1991.

EAS Engineering Automation Systems GmbH. Leegoo builder - engineering edition, 2009.

M. Efroymson and T. Ray. A branch and bound algorithm for plant location. *Operations Research*, 14:361–368, 1996.

R. Ellsworth. Cost to capacity factor development for facility projects. *Cost engineering / American Association of Cost Engineers, AACE*, 49(9):26–30, 2007.

K. Ferdows. Making the most of foreign factories. *Harvard Business Review*, 75: 73–88, 1997.

M. Fischetti, A. Lodi, and P. Toth. Solving real-world atsp instances by branch-and-cut. *Lecture Notes In Computer Science*, pages 64–77, 2003.

B. Flyvbjerg, N. Bruzelius, and W. Rothengatter. *Megaprojects and Risk: An Anatomy of Ambition*. Cambridge University Press, 2003.

J. J. H. Forrest, J. P. H. Hirst, and J. A. Tomlin. Practical solution of large mixed integer programming problems with umpire. *Management Science*, 20(5):736–773, 1974.

J. Fraher and G. Thesing. German december orders decline, led by consumer goods, 2007.

J. Fransoo and D. V. Donk. Call for papers. *Journal of Operations Management*, 21:249–250, 2003.

R. Ganeshan and T. Harrison. An introduction to supply chain management, 1995.

A. M. Geoffrion and G. Graves. Multicommodity distribution system design by benders decomposition. *Management Science*, 29 (5):822–844, 1974.

A. Gerrard. *Guide to capital cost estimating, 4 Edition*. Institute of Chemical Engineers, 2000.

J. Gido and J. Clements. *Successful Project Management*. South-western College, 1999.

O. Günlük. A branch-and-cut algorithm for capacitated network design problems. *Mathematical Programming*, 86(1):17–39, 1999.

B. Günter. Local Content - eine Herausforderung für das internationale Marketing. *Marketing, Zeitschrift für Forschung und Praxis*, 4:263–274, 1985.

K. Gottwald, V. Stroh, and T. Waldmann. Rekord im Ausland - Investitionsschwäche im Inland, Lagebericht der Arbeitsgemeinschaft Großanlagenbau, 2005.

K. Gottwald, V. Stroh, and T. Waldmann. Anhaltender Auftragsboom - Neue Herausforderungen, Lagebericht der Arbeitsgemeinschaft Großanlagenbau, 2007.

K. Gottwald, V. Stroh, and T. Waldmann. Weltweite Erfolge - Ressourcen schonende Technologien für den globalen Markt, Lagebericht der Arbeitsgemeinschaft Großanlagenbau, 2008.

K. Gottwald, V. Stroh, and T. Waldmann. Herausforderndes Umfeld - Politische Rahmenbedingungen verbessern, Lagebericht der Arbeitsgemeinschaft Großanlagenbau, 2009.

C. Gray and E. Larson. *Project Management: The Managerial Process*. McGraw-Hill, 2008.

G. Grossman. The theory of domestic content protection and content preference. *The Quarterly Journal of Economics*, 96, 4:583–603, 1981.

S. Hartmann. *Project Scheduling under Limited Resources*. Springer-Verlag, 1999.

R. Heilmann. A branch-and-bound procedure for the multi-mode resource-constrained project scheduling problem with minimum and maximum time lags. *European Journal of Operational Research*, 144(2):348–365, 2003.

F. Helmus. *Process Plant Design - Project Management from Inquiry to Acceptance*. Wiley-VCH, 2008.

W. Herroelen. Resource-constrained project scheduling-the state of the art. *Operations Research Quarterly*, 23:261–275, 1972.

E. Heymann. Dynamische Branchen begünstigen globale Wachstumszentren, 2005.

K. Holmberg and D. Yuan. A lagrangean heuristic based branch-and-bound approach for the capacitated network design problem. *Operations Research*, 48(3):461–481, 2000.

K. Humphreys. *Project and Cost Engineers' Handbook*. CRC, 2004.

K. Humphreys and P. Wellman. *Basic Cost Engineering, 3rd Edition*. Marcel Dekker, Inc., 1996.

IBM internal material. Project management orientation, 2001.

A. Ilgen. *Wissensmanagement im Großanlagenbau: Ganzheitlicher Ansatz und empirische Prüfung*. 2001.

J. Kagel and D. Levin. *Common Value Auctions and the Winner's Curse*. Princeton University Press, 2002.

R. Karp. Reducibility among combinatorial problems. In R. Miller and J. Thatcher, editors, *Complexity of computer allications*, pages 85–104. Plenum Press, New York, 1972.

J. Kelley. Critical-path planning and scheduling: Mathematical basis. *Operations Research*, 9:296–320, 1961.

J. Kelley. The critial-path method: Resources planning and scheduling. In *Industrial Scheduling*, pages 347–365. Prentice-Hall, New Jersey, 1963.

H. Kerzner. Project management: A systems approach to planning, scheduling, and controlling, 2005.

H. Kerzner. *Project Management: A Systems Approach to Planning, Scheduling, and Controlling, 10 Edition*. Wiley, 2009.

O. Kharbanda and E. Stallworthy. *How to Learn From Project Disasters: True-Life Horror Stories With a Moral for Management*. Ashgate, 1983.

O. Kharbanda and E. Stallworthy. *Capital cost estimating for the process industries*. Butterworth, 1988.

T. Kloppenborg and W. Opfer. The current state of project management research: trends, interpretations, and predictions. *Project Management Journal*, 33 (2): 5–18, 2002.

R. Kolisch. Serial and parallel resource-constrained project scheduling methods revisited: Theory and computation. *European Journal of Operational Research*, 90(2):320–333, 1996.

R. Kolisch. *Project Scheduling under Resource Constraints*. 1995.

R. Kolisch and S. Hartmann. Heuristic algorithms for the resource-constrained project scheduling problem: Classification and computational analysis. In J.Weglarz, editor, *Project Scheduling: Recent Models, Algorithms and Applications*, pages 147–178. Kluwer Academic, Amsterdam, 1998.

R. Kolisch and A. Sprecher. PSPLIB - a project scheduling problem library. *European Journal of Operational Research*, 96:205–216, 1996.

R. Kolisch, A. Sprecher, and A. Drexl. Characterization and generation of a general class of resource-constrained project scheduling problems, 1992.

R. Kolisch, A. Sprecher, and A. Drexl. Characterization and generation of a general class of resource-constrained project scheduling problems. *Management Science*, 41(10):1693–1703, 1995.

R. Kolisch, A. Sprecher, and C. Schwindt. Benchmark instances for project scheduling problems. In J. Weglarz, editor, *Handbook on recent advances in project scheduling*, pages 197–212. Kluwer, 1999.

P. Krugman and M. Obstfeld. *International Economics: Theory and Policy, 8 Edition*. Longman, 2008.

A. Land and A. Doig. An automatic method of solving discrete programming problems. *Econometrica*, 28(3):497–520, 1960.

H. Lang. Engineering approach to preliminary cost estimates. *Chemical Engineering*, 54:130–133, 1947.

C. Lion. Trade-related investiment measures. *Business America*, 115:9–10, 1994.

D. Lock. *Project Management in Construction*. Gower Publishing Limited, 2004.

D. Lock. *Project management*. Gower Publishing Limited, 2007.

R. Martin. *Large Scale Linear and Integer Optimization*. Kluwer Academic Publishers, 1999.

H. Maynard and K. Zandin. *Maynard's Industrial Engineering Handbook*. McGraw-Hill Professional, 2001.

M. Meixell and V. Gargeya. Global supply chain design: A literature review and critique. *Transportation Research Part E*, 41:531–550, 2005.

C. Munson and M. J. Rosenblatt. The impact of local content rules on global sourcing decisions. *Production and Operations Management*, 6, 3:277–290, 1997.

J. Murphy. *Guide To Contract Pricing: Cost and Price Analysis for Contractors, Subcontractors, and Government Agencies*. Management Concepts Inc, 2004.

R. Nauss. An improved algorithm for the capacitated facility location problem. *The Journal of the Operational Research Society*, 29(12):1195–1201, 1978.

K. Neumann, C. Schwindt, and J. Zimmermann. *Project Scheduling with Time Windows and Scarce Resources*. 2003.

H. Orr, J. Sponner, and R. Stutz. The development and implementation of computer assistance for cost estimating. *Cost Engineering*, 21(5):177–182, 1978.

N. Pascheuer, M. Jünger, and G. Reinelt. A branch & cut algorithm for the asymmetric traveling salesman problem with precedence constraints. *Computational Optimization and Applications*, 17(1):61–84, 2000.

J. Patterson and W. Huber. A horizon-varying, zero-one approach to project scheduling problem. *Management Science*, 20:990–998, 1974.

J. Patterson and G. Roth. Scheduling a project under multiple resource constraints: A zero-one programming approach. *AIIE Transactions*, 8:449–455, 1976.

J. Pinto and D. Slevin. Critical success factors across the project life cycle. *Project Management Journal*, 19(2):68–75, 1998.

PMI. *A Guide to the Project Management Body of Knowledge, 4 Edition*. Project Management Institute, 2008.

A. Pritsker and W. Happ. Graphical evaluation and review technique. part i. fundamentals. *The Journal of Industrial Engineering*, 17(5):267–274, 1966.

Research and Markets. Process plant industry market review, 2000.

B. Schiemenz. Systemtheorie. In H. Corsten, editor, *Lexikon der Betriebswirtschaftslehre*, pages 831–835. 1992.

T. Schiller. *Kompetenz-Management für den Anlagenbau: Ansatz, Empirie und Aufgaben*. 2000.

C. Scott-Young and D. Samson. Project success and project team management: Evidence from capital projects in the process industries. *Journal of Operations Management*, 26:749–766, 2008.

E. Senne, L. Lorena, and M. Pereira. A branch-and-price approach to p-median location problems. *Computers and Operations Research*, 32(6):1655–1664, 2005.

A. Shtub, J. Bard, , and S. Globerson. *Project Management: Engineering, Technology and Implementation*. Prentice Hall, 1994.

R. Sinnott. *Chemical Engineering Design, 4 Edition*. Butterworth-Heinemann Ltd., 2005.

N. Smith. *Project cost estimating*. Thomas Telford Ltd, 1995.

M. Spinner. *Project Management - Principles and Practices*. Prentice-Hall, 1997.

A. Sprecher and A. Drexl. Solving multi-mode resource-constrained project scheduling problems by a simple, general and powerful sequencing algorithm. *European Journal of Operational Research*, 107:431–450, 1998.

A. Sprecher, R. Kolisch, and A. Drex. Semi-active, active, and non-delay schedules for the resource-constrained project scheduling problem. *European Journal of Operational Research*, 80:94–102, 1995.

L. Stuckenbruck. *The Implementation of Project Management*. Project Management Institute, 1981.

F. Talbot. Resource-constrained project scheduling with time-resource tradeoffs: the non preemptive case. *Management Science*, 28:1197–1210, 1982.

The World Bank. Procurement of works - standard bidding documents, 2006.

UNIDO. Industrial policies and strategies in developing countries: An analysis of local content regulations, 1986.

V. Valls, M. Pérez, and M. Quintanilla. Heuristic performance in large resource-constrained projects, 1992.

VDI. *Angebotserstellung in der Investitionsgüterindustrie*. VDI-Verlag GmbH, 1983.

G. Vickery. Global industries and national policies. *OECD Observer*, 179:11–14, 1993.

C. Vidal and M. Goetschalckx. A global supply chain model with transfer pricing and transportation cost allocation. *European Journal of Operational Research*, 129:134–158, 2001.

P. Watermeyer. *Handbook for Process Plant Project Engineers*. Wiley, 2002.

M. Wideman. *The Role of the Project Life Cycle (Life Span) in Project Management*. 2004.

M. Wideman. Wideman comparative glossary of project management terms, 2006.

Wirtschaft aktuell. Außenhandel - Entwicklung 2008 und Perspektive 2009, 2009.

A. Zobel and S. Wearne. Project management topic coverage in recent conferences. *Project Management Journal*, 31(2):32–37, 2000.